TRAINING COURSE IN GEOTECHNICAL AND FOUNDATION ENGINEERING

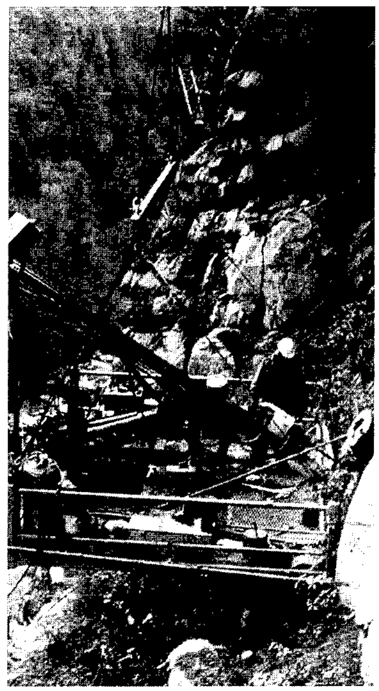
PB99-146573

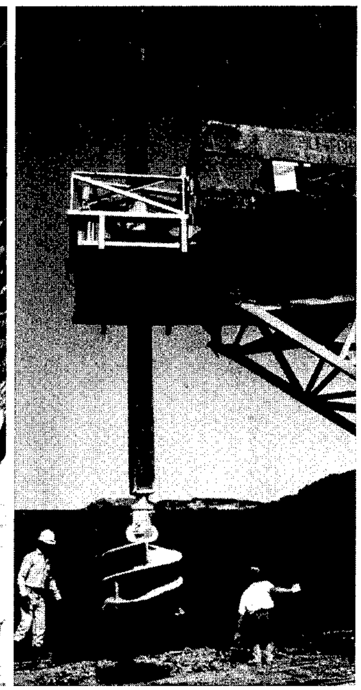
NHI COURSE NO. 13236 - MODULE 6

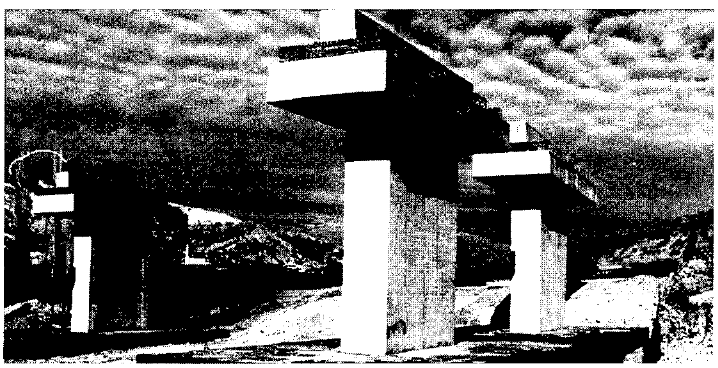
PUBLICATION NO. FHWA NHI-99-026
JUNE 1999

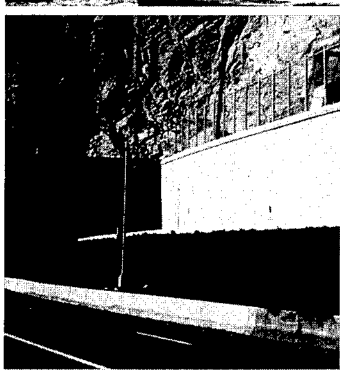
EARTH RETAINING STRUCTURES

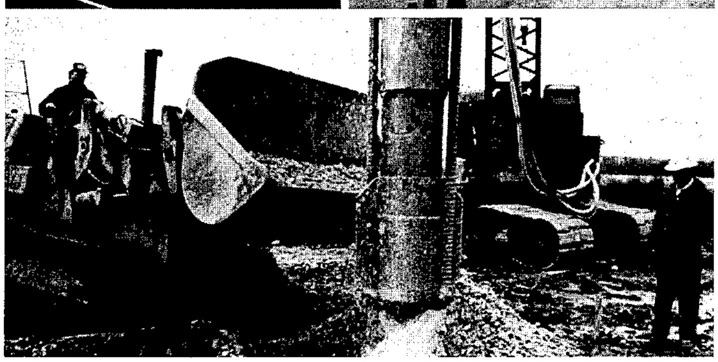
STUDENT EXERCISES











U.S. Department
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THIS STUDENT EXERCISE BOOK (FHWA-NHI-99-026) IS INTENDED ONLY TO BE USED AS AN INTERACTIVE TEACHING TOOL FOR NHI COURSE NO. 13236 – MODULE 6 "EARTH RETAINING STRUCTURES", AND IS NOT INTENDED TO BE USED AS AN INDIVIDUAL EXERCISE BOOK.

DETAILED DESIGN EXAMPLES ILLUSTRATING THE PRINCIPLES AND ANALYSES OF EARTH RETAINING STRUCTURES ARE INCLUDED IN THE REFERENCE MANUAL (FHWA-NHI-99-025) FOR THE SAME COURSE.

TRAINING COURSE IN GEOTECHNICAL
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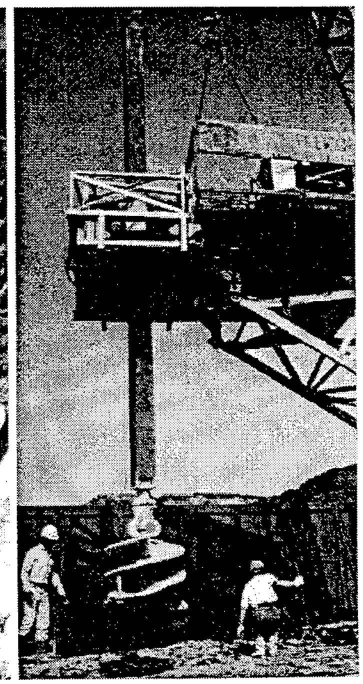
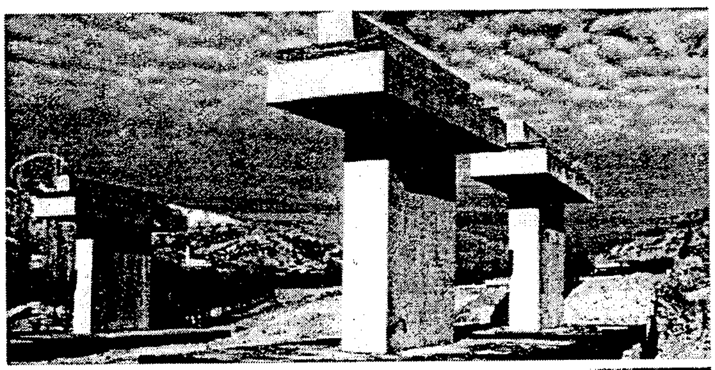
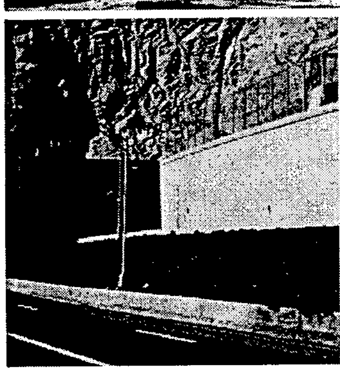


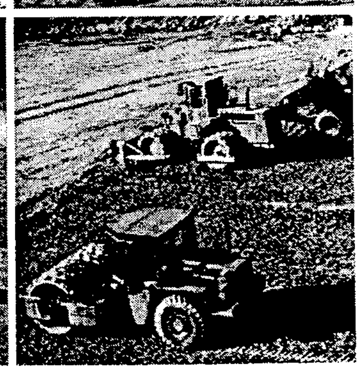
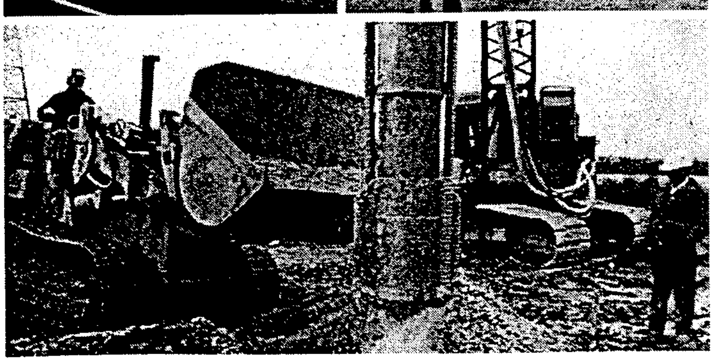

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16. Abstract

This student exercise book has been developed for use as an interactive teaching tool and a companion workbook for NHI Course No. 13236 - Module 6 "Earth Retaining Structures", and is not intended to be used as an individual exercise book. The extents and depths of the problems presented in this exercise book are limited due to the time constraint of the 3-day course schedule. Detailed design examples illustrating the principles and analyses of each wall type are included in Module 6 "Earth Retaining Structures" Reference Manual (FHWA-NHI-99-025).

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Retaining walls, earth, groundwater, anchors, stabilized, gravity, analysis, design, construction, lateral pressures, in situ, contracting, bidding, transportation, highways, bridges.	No restrictions.

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PREFACE

This student exercise book is intended only to be used as an interactive teaching tool and a companion workbook for NHI Course No. 13236 - Module 6 "Earth Retaining Structures", and is not intended to be used as an individual exercise book. The extents and depths of the problems presented in this exercise book are limited due to the time constraint of the 3-day course schedule.

Module 6 "Earth Retaining Structures" is the sixth module in a series of twelve modules that constitute a comprehensive training course in geotechnical and foundation engineering. Sponsored by the National Highway Institute (NHI) of the Federal Highway Administration (FHWA), the training course is given at different locations in the U.S. The targeted audience for the course includes civil engineers and engineering geologists who are involved in the analysis, design, and construction of surface transportation facilities in seismic areas.

A reference manual (FHWA-NHI-99-025) was developed to provide the practicing engineers with a thorough understanding of the various types of retaining walls; detailed analytical and design procedures; discussions of wall selection, contracting issues, bidding documents; and case histories involving selection, design, construction and performance of earth retaining structures for highway applications. Detailed design examples are also included in the reference manual.

Finally, this student exercise book is developed to be used as a living document. Additional student exercises or case histories may be given separately during the training session.

NOTICE

The information in this document has been funded wholly or in part by the US Department of Transportation, Federal Highway Administration (FHWA), under Contract No. DTFH 61-94-C-00104 to Parsons Brinckerhoff Quade & Douglas, Inc. The document has been subjected to peer and administrative review by FHWA, and it has been approved for publication as a FHWA document.

CONVERSION FACTORS

Approximate Conversions to SI Units			Approximate Conversions from SI Units		
When you know	Multiply by	To find	When you know	Multiply by	To find
(a) Length					
inch	25.4	millimeter	millimeter	0.039	inch
foot	0.305	meter	meter	3.28	foot
yard	0.914	meter	meter	1.09	yard
mile	1.61	kilometer	kilometer	0.621	mile
(b) Area					
square inches	645.2	square millimeters	square millimeters	0.0016	square inches
square feet	0.093	square meters	square meters	10.764	square feet
acres	0.405	hectares	hectares	2.47	acres
square miles	2.59	square kilometers	square kilometers	0.386	square miles
(c) Volume					
fluid ounces	29.57	milliliters	milliliters	0.034	fluid ounces
gallons	3.785	liters	liters	0.264	gallons
cubic feet	0.028	cubic meters	cubic meters	35.32	cubic feet
cubic yards	0.765	cubic meters	cubic meters	1.308	cubic yards
(d) Mass					
ounces	28.35	grams	grams	0.035	ounces
pounds	0.454	kilograms	kilograms	2.205	pounds
short tons (2000 lb)	0.907	megagrams (tonne)	megagrams (tonne)	1.102	short tons (2000 lb)
(e) Force					
pound	4.448	Newton	Newton	0.2248	pound
(f) Pressure, Stress, Modulus of Elasticity					
pounds per square foot	47.88	Pascals	Pascals	0.021	pounds per square foot
pounds per square inch	6.895	kiloPascals	kiloPascals	0.145	pounds per square inch
(g) Density					
pounds per cubic foot	16.019	kilograms per cubic meter	kilograms per cubic meter	0.0624	pounds per cubic feet
(h) Temperature					
Fahrenheit temperature(°F)	5/9(°F- 32)	Celsius temperature(°C)	Celsius temperature(°C)	9/5(°C)+ 32	Fahrenheit temperature(°F)

Notes: 1) The primary metric (SI) units used in civil engineering are meter (m), kilogram (kg), second(s), newton (N) and pascal ($Pa=N/m^2$).
2) In a "soft" conversion, an English measurement is mathematically converted to its exact metric equivalent.
3) In a "hard" conversion, a new rounded metric number is created that is convenient to work with and remember.

MODULE 6
EARTH RETAINING STRUCTURES
TABLE OF CONTENTS

STUDENT EXERCISES

STUDENT EXERCISE 1

A 7 km four-lane highway through a mountainous terrain has been proposed by a State DOT. The subsurface investigation program revealed that the soil conditions vary along the alignment. At Station 0 + 50, the soil profile is as shown in Figure S1-1. The soil parameters based on laboratory tests at this location are shown in Figure S1-1.

A cut 6 m deep is required to construct the highway. The designer selected a cantilever wall to retain the 6 m deep cut. Assume a wall with a smooth face.

For the 6 m deep wall:

(a) Determine the active force per unit length of the wall,

(b) Determine the location of the resultant line of action.

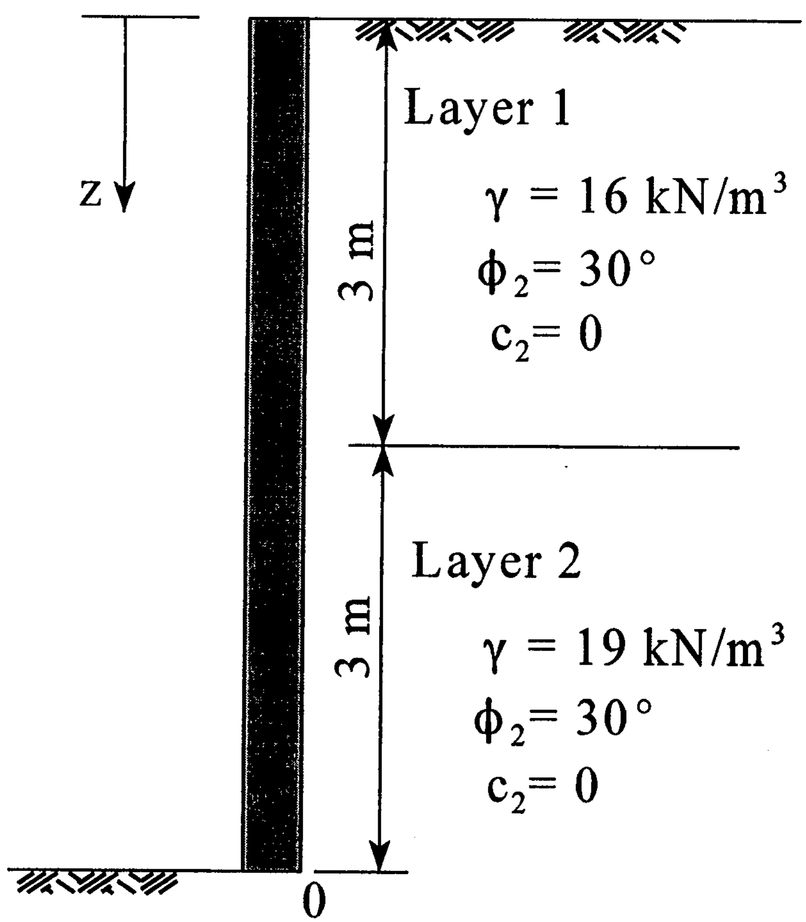
Manual Reference:

Section 2.4, Eq. 2-5,

Figures 2-3 and 2-7.

Student Exercise 1

Figure S1-1



Solution to Student Exercise 1

Compute K_a ***(Eq. 2-5)***

$$K_{a1} = \tan^2 (45° - \phi_1/2)$$
$$= \tan^2 (45° - 30°/2) \quad = 1/3$$

$$K_{a2} = \tan^2 (45° - \phi_2/2)$$
$$= \tan^2 (45° - 30°/2) \quad = 1/3$$

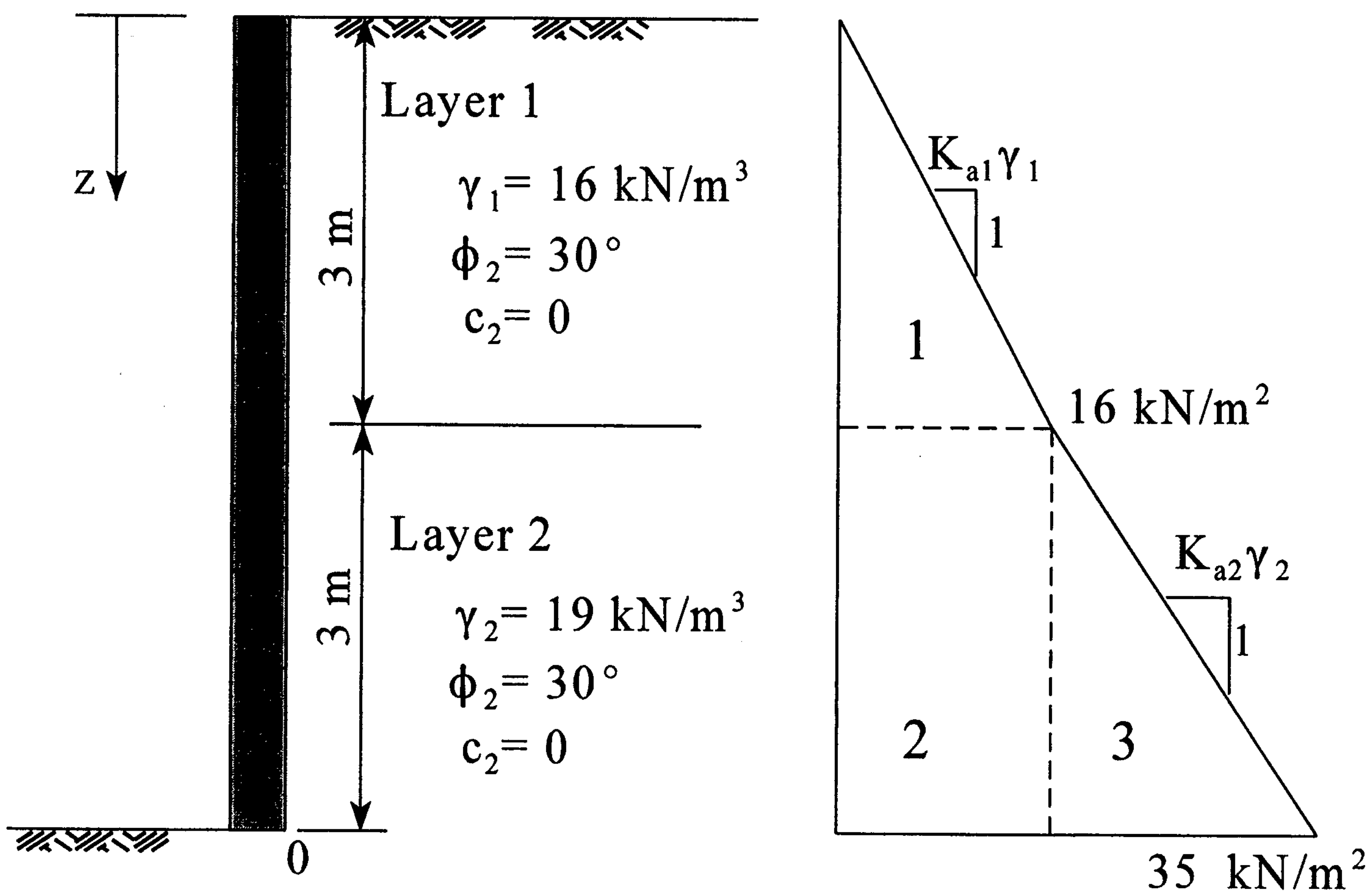
Compute lateral active pressures as follows:

(Figures 2-3 and 2-7)

z, m	σ_{vo}, kN/m^2		Lateral pressure, p_a, kN/m^2		
0	0		$K_{a1}\ \sigma_{vo}$ =	0	0
3^-	(16)(3) =	48	$K_{a1}\ \sigma_{vo}$ =	(1/3)48 =	16
3^+	(16)(3) =	48	$K_{a2}\ \sigma_{vo}$ =	(1/3)48 =	16
6	48 + (19)3=	105	$K_{a2}\ \sigma_{vo}$ =	(1/3)105 =	35

Figure S1-2 shows the lateral earth pressure diagram.

Student Exercise 1 — Figure S1-2



(a) (b)

Total active force per unit length of the wall is equal to the area of the pressure diagram ***(Figure 2-7)***

$$
\begin{aligned}
P_a &= P_1 + P_2 + P_3 \\
&= \text{Area 1} + \text{Area 2} + \text{Area 3} \\
&= \tfrac{1}{2}(3)(16) + (16)(3) + \tfrac{1}{2}(35 - 16)(3) \\
&= 24 + 48 + 28.5 \\
&= \mathbf{100.5\ kN/m}
\end{aligned}
$$

Location of the center of pressure measured from bottom of the wall (point O): ***(Figure 2-7)***

$$\bar{z} = \frac{P_1 L_1 + P_2 L_2 + P_3 L_3}{P_a}$$

$$\bar{z} = \frac{24\left(3 + \frac{3}{3}\right) + 48\left(\frac{3}{2}\right) + 28.5\left(\frac{3}{3}\right)}{100.5}$$

$$\bar{z} = 1.96\ \text{m}$$

Key Points

- $p_h = K\sigma_{vo}$

  $= (K\gamma)\ z$

  $= (\text{Slope})\ z$

- $K\gamma$ is the slope of the earth pressure diagram.

- The slope of the earth pressure diagram changes in direct proportion to the unit weight of the soil.

- $p_h = (K\gamma)\ z$

  $u = (\gamma_w)\ z$

- $K\gamma$ is similar to γ_w and has same dimensions.

- The quantity $K\gamma$ can be referred to as the ***Equivalent Fluid Unit Weight.***

- Structural designers prefer Equivalent Fluid Unit Weights for design purposes.

STUDENT EXERCISE 2

The soil profile at Station 1+25 is also layered as in Student Exercise 1 but laboratory tests reveal that the bottom layer has $\phi = 36°$ as shown in Figure S2-1.

For the cantilever wall to retain the 6 m deep cut:

(a) Compute the active force per unit length of the wall

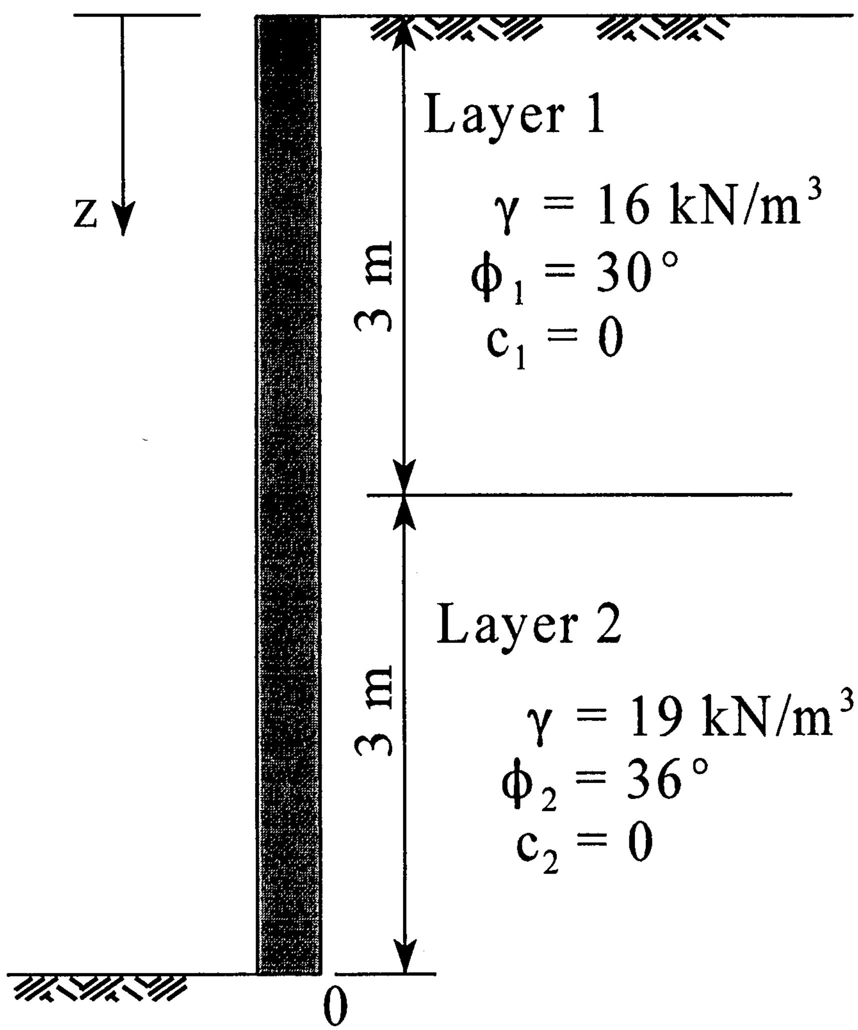
(b) Determine the location of the resultant line of action

Manual Reference:

Section 2.4, Eq. 2-5,

Figures 2-3 and 2-7.

Student Exercise 2 Figure S2-1



Solution to Student Exercise 2

Compute K_a ***(Eq. 2-5)***

$$K_{a1} = \tan^2 (45° - 30°/2) = 1/3$$

$$K_{a2} = \tan^2 (45° - 36°/2) = 0.26$$

Compute lateral pressures as follows:

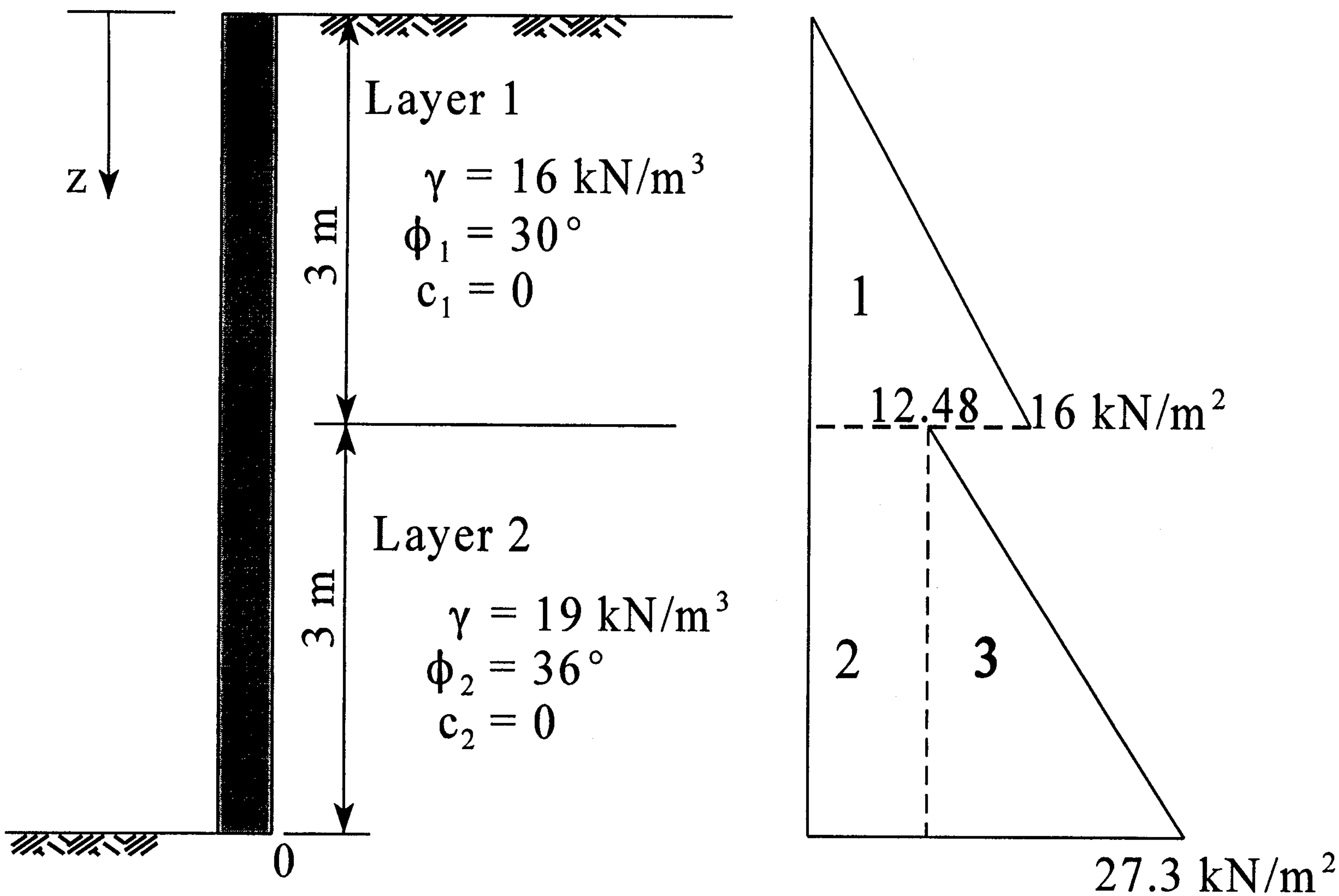
(Figures 2-3 and 2-7)

z, m	σ_{vo}, kN/m^2			Lateral pressure, p_a, kN/m^2			
0	0			$K_{a1}\ \sigma_{vo} =$	0		0
3^-	(16)(3)	=	48	$K_{a1}\ \sigma_{vo} =$	(1/3)48	=	16.00
3^+	(16)(3)	=	48	$K_{a2}\ \sigma_{vo} =$	0.26(48)	=	12.48
6	48+(19)3	=	105	$K_{a2}\ \sigma_{vo} =$	0.26(105)	=	27.30

Figure S2-2 shows the lateral earth pressure diagram.

Student Exercise 2

Figure S2-2



(a) (b)

Total active force per unit length of the wall is equal to the area of the pressure diagram ***(Figure 2-7)***

$$
\begin{aligned}
P_a &= P_1 + P_2 + P_3 \\
&= \text{Area 1} + \text{Area 2} + \text{Area 3} \\
&= \tfrac{1}{2}(3)(16) + (12.48)(3) + \tfrac{1}{2}(27.3 - 12.48)(3) \\
&= 24 + 37.44 + 22.23 \\
&= \mathbf{83.67\ kN/m} \qquad \mathbf{<100.5\ kN/m\ in\ Exercise\ 1}
\end{aligned}
$$

Location of the center of pressure measured from bottom of the wall (point O): ***(Figure 2-7)***

$$\bar{z} = \frac{P_1 L_1 + P_2 L_2 + P_3 L_3}{P_a}$$

$$\bar{z} = \frac{24\left(3 + \frac{3}{3}\right) + 37.44\left(\frac{3}{2}\right) + 22.23\left(\frac{3}{3}\right)}{83.67}$$

$$\bar{z} \simeq 2.0\ \text{m} \qquad \approx \mathbf{1.96\ m\ in\ Exercise\ 1}$$

Key Points

- Two values of earth pressure occur at locations where the shear strength properties of soils change.

- Active earth forces in granular soils are inversely proportional to the friction angle.

If $\phi_1 < \phi_2$ then $K_{a1} > K_{a2}$

Since $p_a \propto K_a$ it follows that $p_{a1} > p_{a2}$

If $p_{a1} > p_{a2}$ then $P_{a1} > P_{a2}$

Thus if $\phi_1 < \phi_2$ then $P_{a1} > P_{a2}$

STUDENT EXERCISE 3

At Station 2+10 along the highway alignment, the local groundwater level rises to a height of 3 m above the bottom of the wall as shown in Figure S3-1. Except the groundwater level the soil profile is same as in Student Exercise 2.

For the case of the 6 m deep cut wall:

(a) Compute the lateral force per unit length of the wall

(b) Determine the location of the resultant line of action

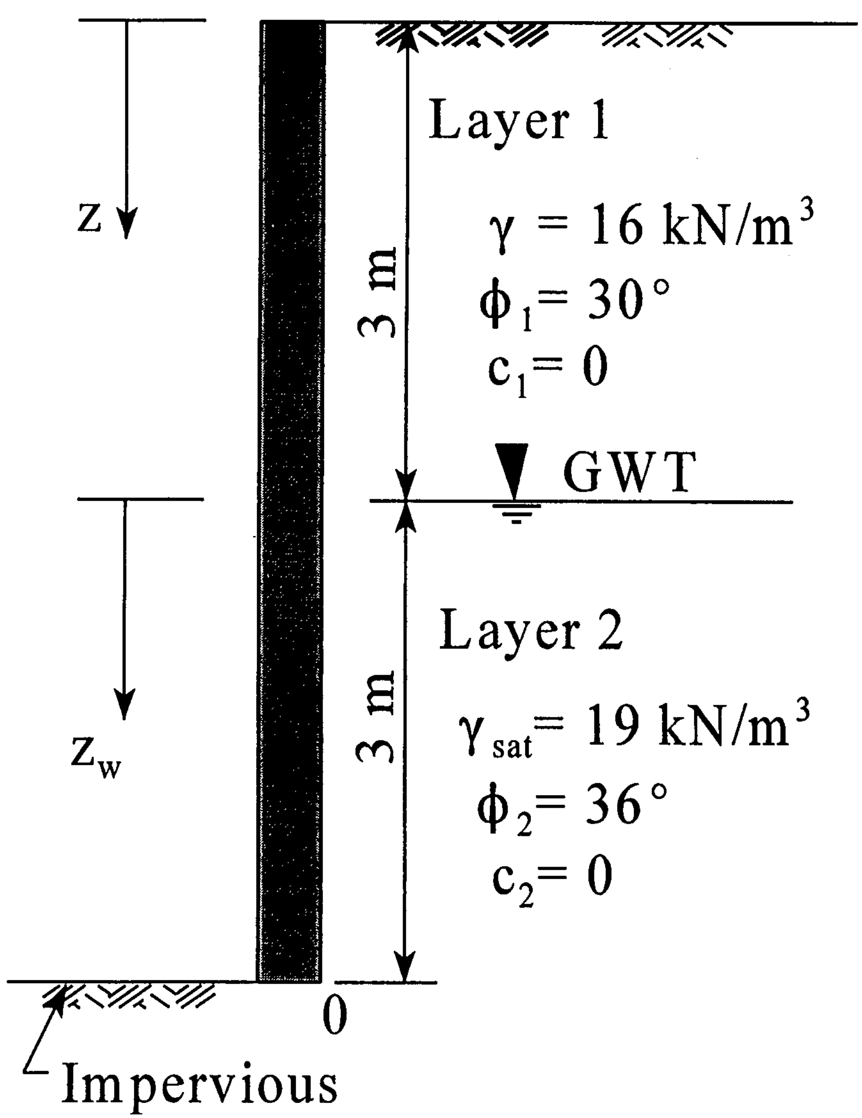
(c) Compare the total lateral force per unit length of the wall with that in Student Exercise 2.

(d) Comment on the effect of water behind wall.

Manual Reference:

Sections 2.4, 2.5; Eq. 2-5; Figures 2-3,2-7 and 2-8; Example Prob 2-1; Footnote on Page 2-1

Student Exercise 3 Figure S3-1



Solution to Student Exercise 3

Compute K_a *(Eq. 2-5)*

$K_{a1} = \tan^2 (45° - 30°/2) = 1/3$

$K_{a2} = \tan^2 (45° - 36°/2) = 0.26$

(Section 2.5, Figure 2-8, Footnote on Page 2-1)

Lateral Pressure = Effective Lateral Earth Pressure
+ Hydrostatic Pressure

$\sigma'_{vo} = \sigma_{vo} - u$ $\gamma' = \gamma_{sat} - \gamma_w$

Effective Lateral Earth Pressures

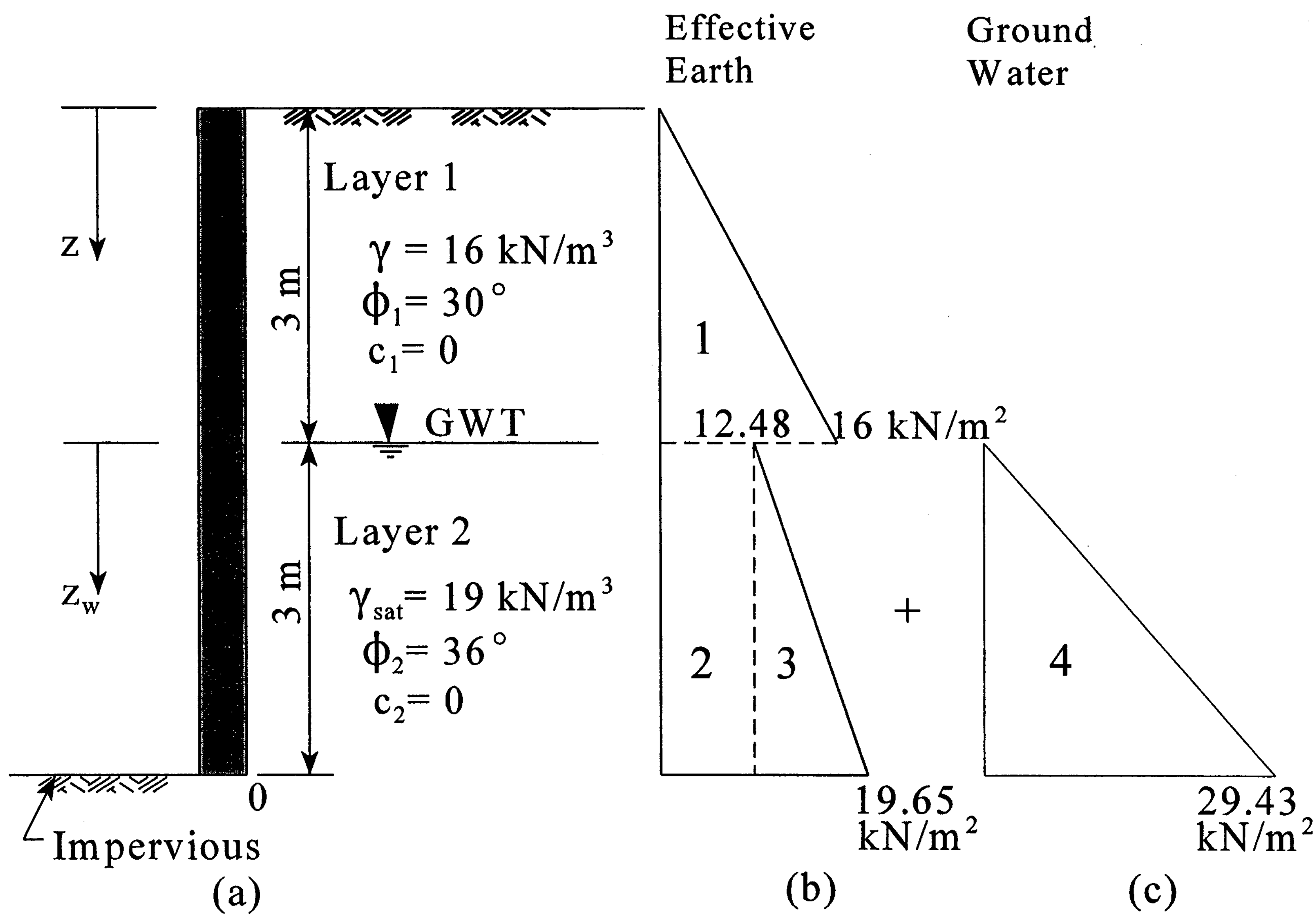
z, m	σ'_{vo}, kN/m^2	Lateral pressure, p_a, kN/m^2
0	0	$K_{a1}\ \sigma'_{vo} =$ 0 0
3^-	(16)(3) = 48	$K_{a1}\ \sigma'_{vo} =$ (1/3)48 = 16.00
3^+	(16)(3) = 48	$K_{a2}\ \sigma'_{vo} =$ 0.26(48) = 12.48
6	48+ (19-9.81)3 = 75.57	$K_{a2}\ \sigma'_{vo} =$ 0.26(75.57) = 19.65

Hydrostatic Pressure, p_w

z, m	z_w, m	$u = z_w \gamma_w$, kN/m^2	Lateral pressure, p_w, kN/m^2
0	0	0	0
3	0	0	0
6	3	3 (9.81) = 29.43	$K_w \sigma_w$ = 1.0(29.43) = 29.43

The lateral pressure diagrams are shown in Figure S3-2.

Student Exercise 3 Figure S3-2



Total lateral force per unit length of the wall is equal to the area of the pressure diagram ***(Figure 2-7)***

$$
\begin{aligned}
P_h &= P_1 + P_2 + P_3 + P_4 \\
&= \text{Area } 1 + \text{Area } 2 + \text{Area } 3 + \text{Area } 4 \\
&= \tfrac{1}{2}(3)(16) + (12.48)(3) \\
&\qquad + \tfrac{1}{2}(19.65 - 12.48)(3) + \tfrac{1}{2}(3)(29.43) \\
&= 24 + 37.44 + 10.76 + 44.15 \\
&= \mathbf{116.35\ kN/m} \qquad \mathbf{> 83.67\ kN/m\ in\ Exercise\ 2}
\end{aligned}
$$

Percent change in lateral force per unit length due to presence of ground water table at a depth of 3 m

$$\text{Percent change} = \frac{116.35 - 83.67}{83.67} \times 100 \simeq 39$$

$$\text{Ratio} = \frac{116.35}{83.67} \simeq 1.39$$

Location of the center of pressure measured from bottom of the wall (point O): ***(Figure 2-7)***

$$\bar{z} = \frac{P_1 L_1 + P_2 L_2 + P_3 L_3 + P_4 L_4}{P_a}$$

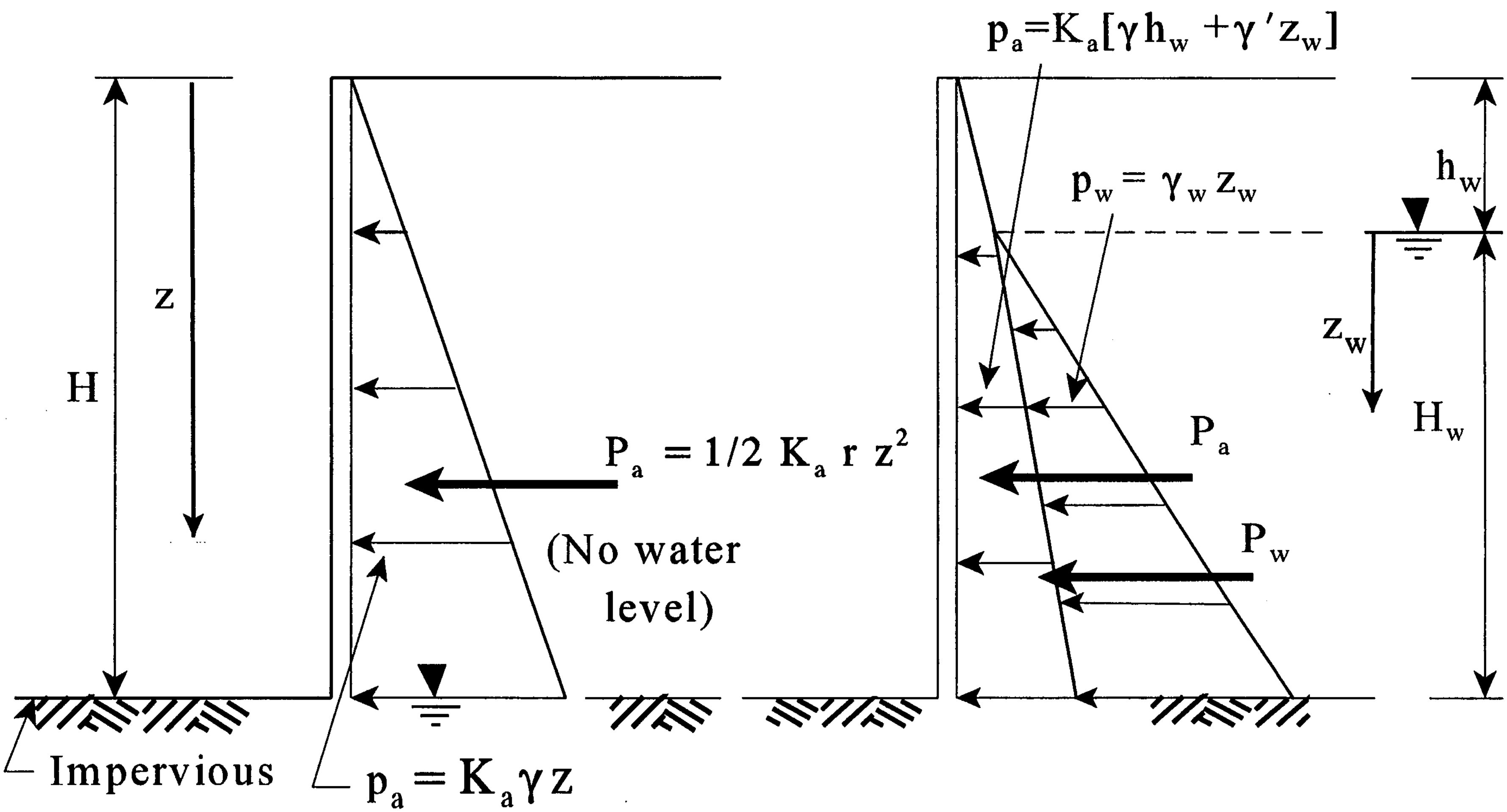
$$\bar{z} = \frac{24\left(3 + \frac{3}{3}\right) + 37.44\left(\frac{3}{2}\right) + 10.76\left(\frac{3}{3}\right) + 44.15\left(\frac{3}{3}\right)}{116.35}$$

$$\bar{z} = 1.78 \text{ m}$$ **< 2 m in Exercises 1 and 2**

(d) Refer to Figure S3-3 (or Figure 2-8 of the Manual).

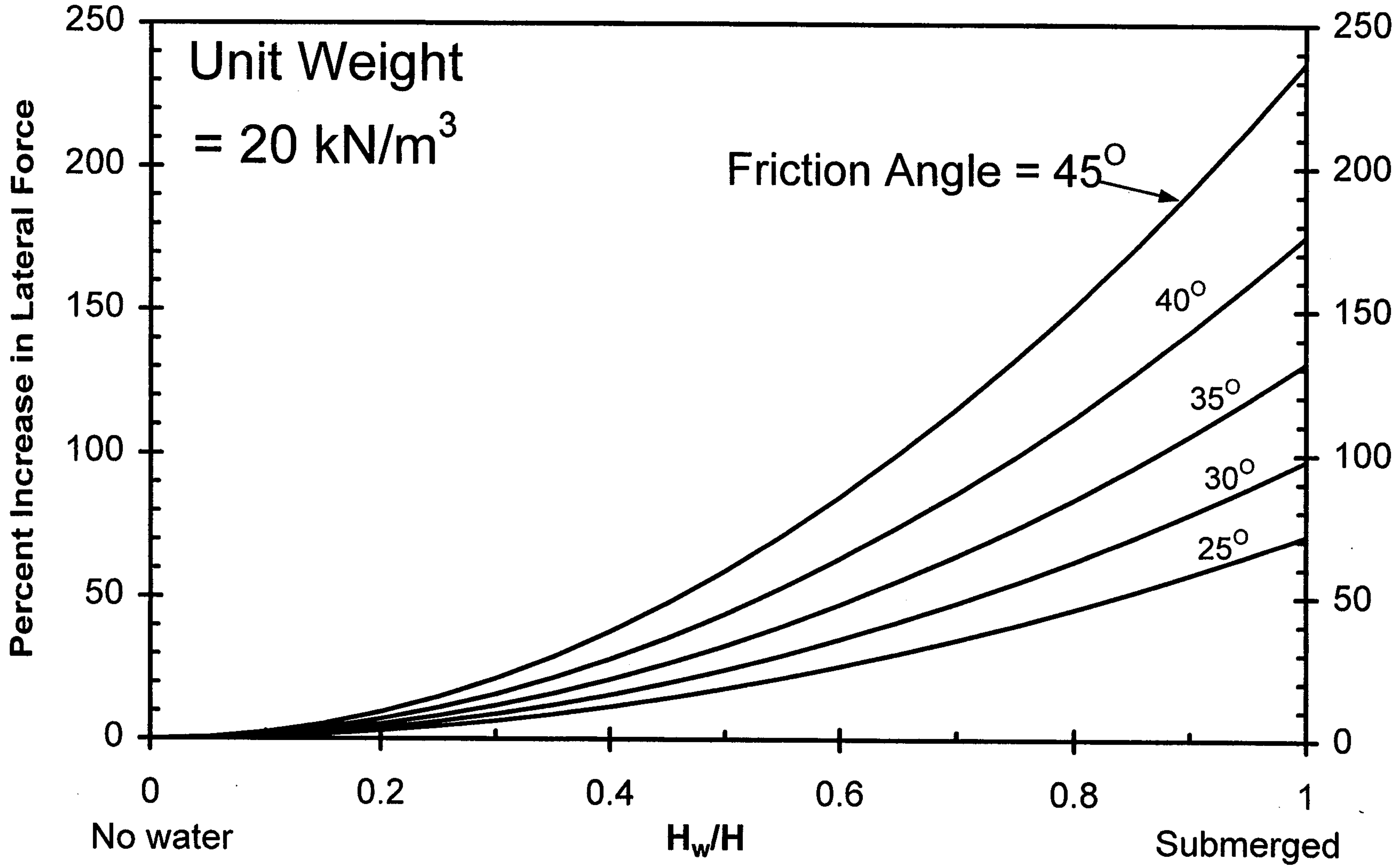
Figures S3-4 and S3-5 show the percent increase in the lateral force versus H_w/H.

Student Exercise 3 *Figure S3-3*



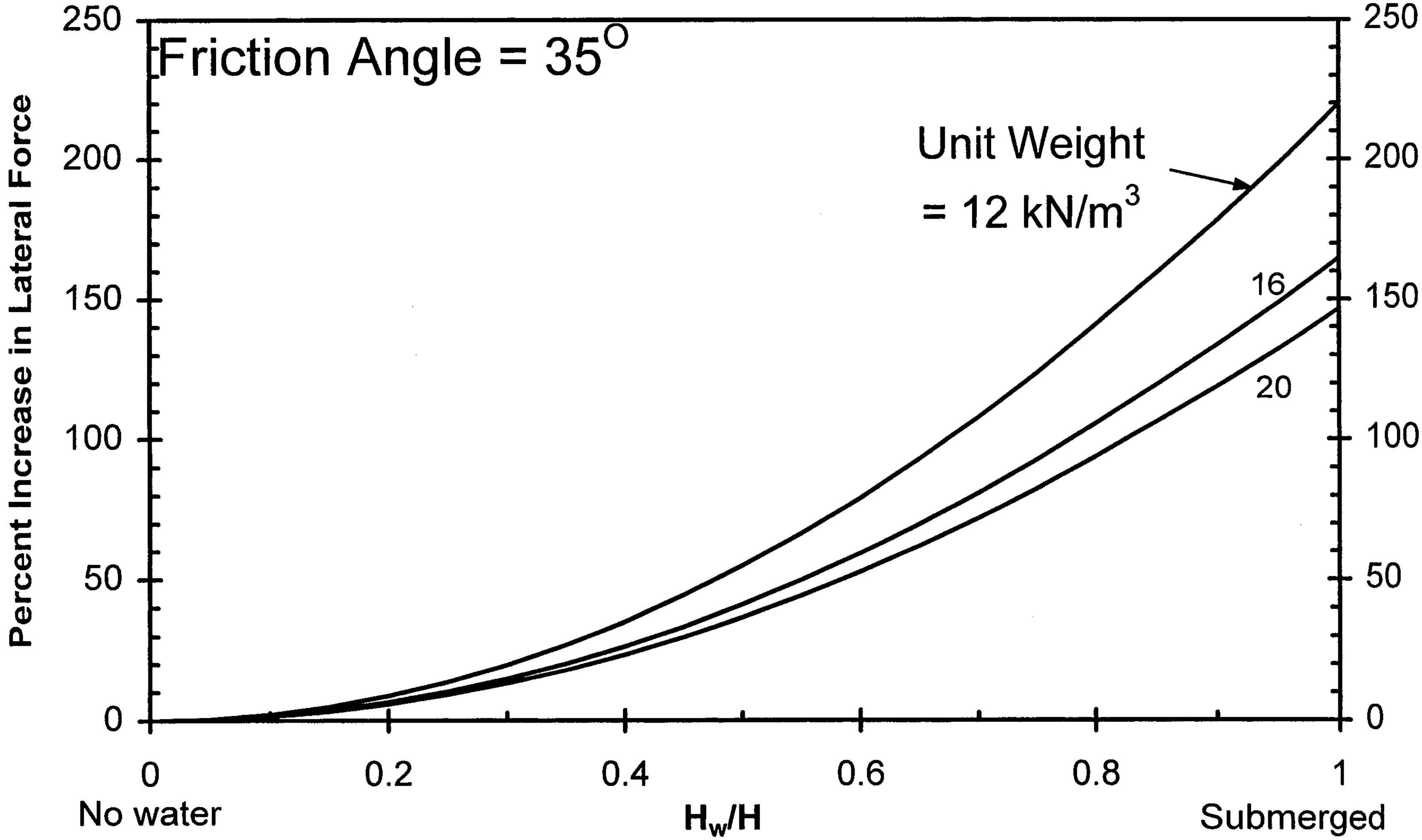
Student Exercise 3 — Figure S3-4

Effect of Water Behind Wall



Student Exercise 3 *Figure S3-5*

Effect of Water Behind Wall



Key Points

- Use effective stresses below water table.
- Presence of free water increases the lateral pressures considerably.
- Due to the significant effect of water, it is customary and advisable to provide drainage measures rather than design the wall for large pressures.

STUDENT EXERCISE 4

From Station 2+90 to 3+60, the soils in Layer 1 were classified as CL. The laboratory tests revealed that while all other quantities remained the same, Layer 1 has a cohesion, c_1, of 9.25 kPa as shown in Figure S4-1.

For the 6 m deep cut wall:

(a) Determine the depth of tensile crack

(b) Determine the total lateral force, P_h, after occurence of the tensile crack

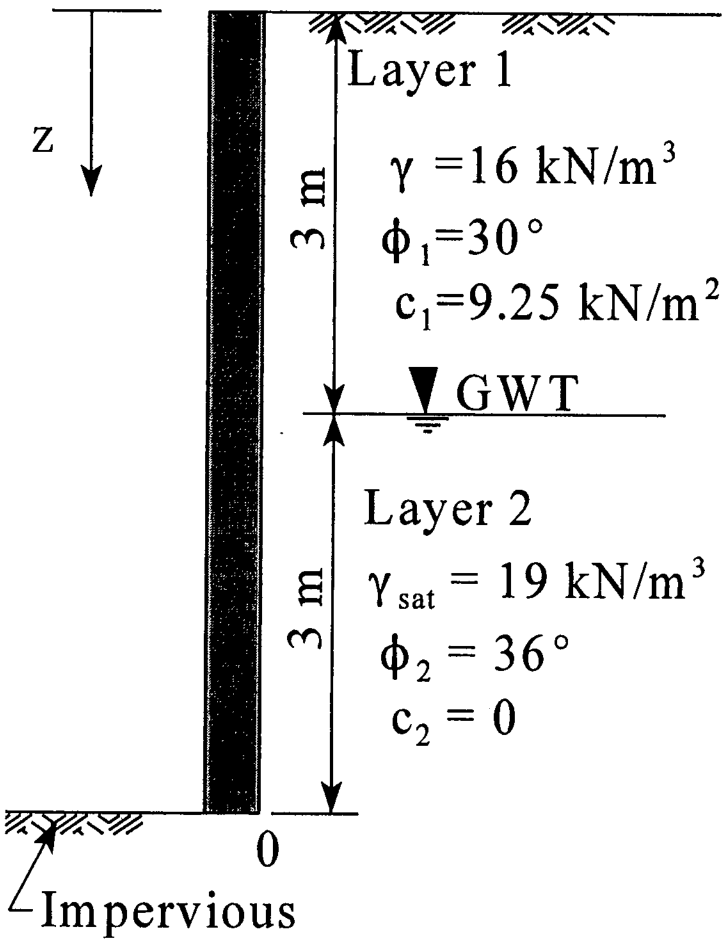
(c) Assume possibility of water infiltration in tensile crack. Determine the total lateral force, P_h.

Manual Reference:

Sections 2.4 and 2.5; Eq. 2-5;

Figures 2-3b, 2-7 and 2-8.

Student Exercise 4 — Figure S4-1



(a)

Solution to Student Exercise 4

Compute K_a ***(Eq. 2-5)***

$$K_{a1} = \tan^2 (45° - 30°/2) = 1/3$$

$$K_{a2} = \tan^2 (45° - 36°/2) = 0.26$$

Compute depth of Tensile Crack

From Figure 2-3b:

$$z_o = \frac{2\,c_1}{\gamma\sqrt{K_{a1}}}$$

$$z_o = \frac{(2)(9.25)}{16\sqrt{(1/3)}} = 2 \text{ m}$$

The pressure diagram up to $z = z_o = 2$ m will be zero.

For $z = 3^{-}$ m, the lateral earth pressure due to clay will be:

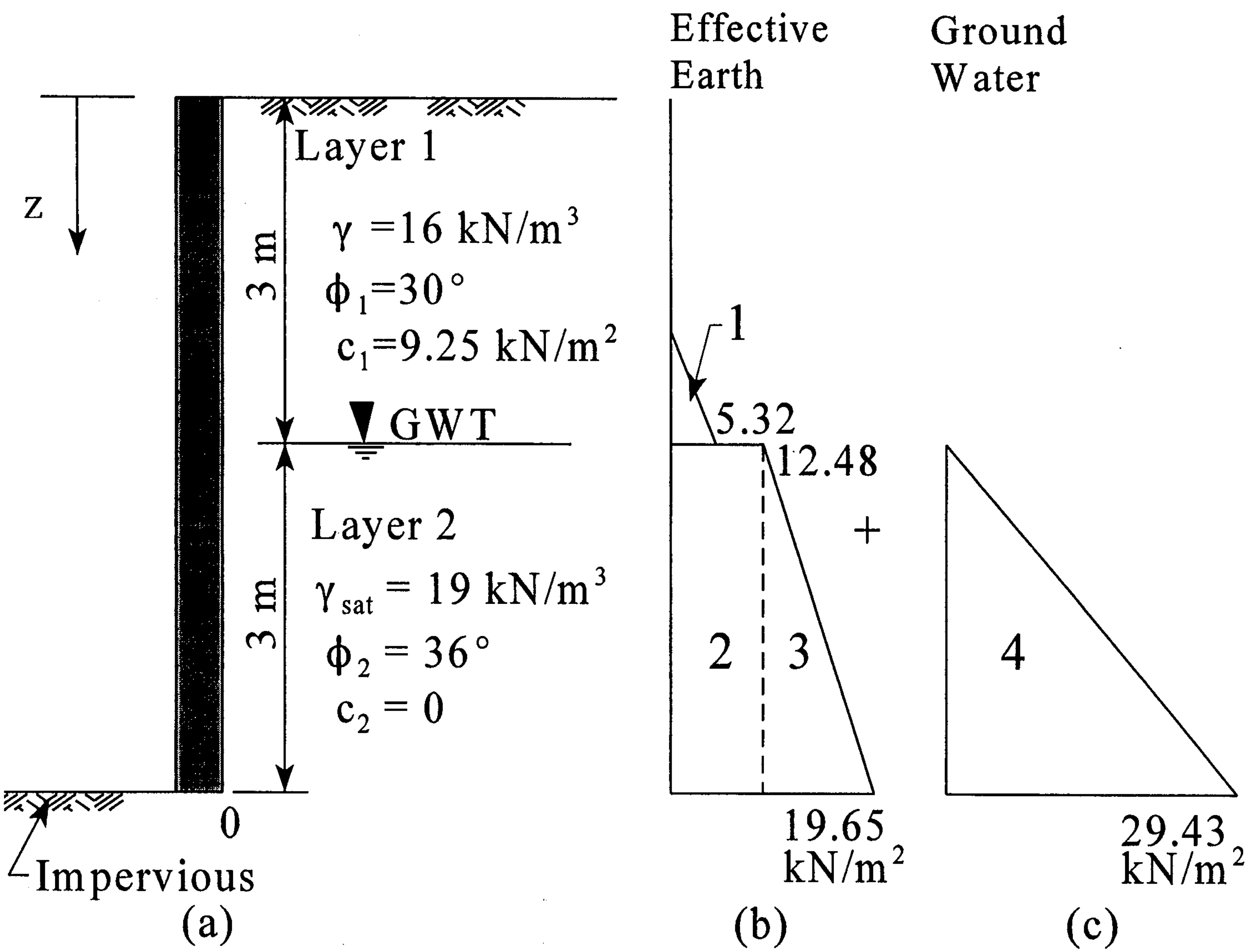
$$p_a = \sigma_v K_{a1} - 2c_1\sqrt{K_{a1}}$$ ***(Figure 2-3b)***

$$p_a = (16)(3)\left(\frac{1}{3}\right) - (2)(9.25)\sqrt{\frac{1}{3}}$$

$$p_a = 5.32 \ \ \mathrm{kN/m^2}$$

For z > 3 m, the lateral pressure diagram (Areas 2, 3 and 4) will be the same as in the previous Workshop Problem as shown in Figure S4-2.

Student Exercise 4 Figure S4-2



Total lateral force P_h is equal to the area of the pressure diagram

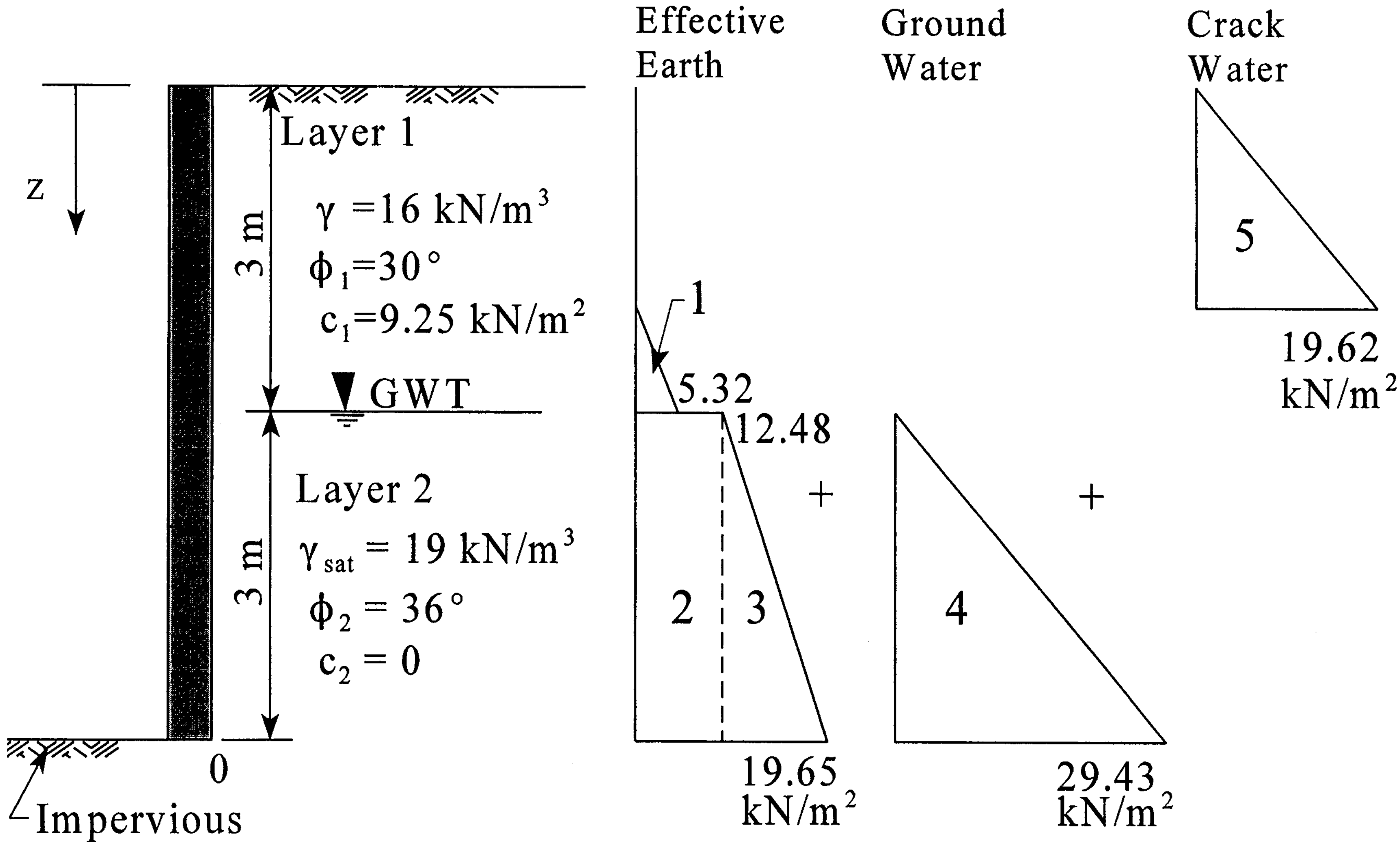
$$
\begin{aligned}
P_h &= P_1 + P_2 + P_3 + P_4 \\
&= \text{Area 1} + \text{Area 2} + \text{Area 3} + \text{Area 4} \\
&= \tfrac{1}{2}(1)(5.32) + \\
&\quad (12.48)(3) + \tfrac{1}{2}(19.65 - 12.48)(3) + \tfrac{1}{2}(3)(29.43) \\
&= 2.66 + 37.44 + 10.76 + 44.15 \\
&= \mathbf{95.01\ kN/m} \qquad \mathbf{< 116.35\ kN/m\ in\ Exercise\ 3}
\end{aligned}
$$

If the tensile crack fills up with water additional lateral pressure will occur up to a depth of 2 m as follows:

$$u_{tc} = (2)(\gamma_w) = (2)(9.81) = 19.62 \ \text{kN/m}^2$$

The lateral pressure diagram for this case is shown in Figure S4-3.

Student Exercise 4 — Figure S4-3



(a) (b) (c) (d)

The lateral force per unit length is equal to the area of the pressure diagram

$$P_h = P_1 + P_2 + P_3 + P_4 + P_5$$

$$= \text{Area 1} + \text{Area 2} + \text{Area 3} + \text{Area 4} + \text{Area 5}$$

$$= \tfrac{1}{2}(1)(5.32) + (12.48)(3) + \tfrac{1}{2}(19.65 - 12.48)(3) + \tfrac{1}{2}(3)(29.43) + \tfrac{1}{2}(2)(19.62)$$

$$= 2.66 + 37.44 + 10.76 + 44.15 + 19.62$$

$$= \mathbf{114.63\ kN/m} \qquad \approx \mathbf{116.35\ kN/m\ in\ Exercise\ 3}$$

Key Points

- $p_a = \sigma_v K_a - 2c\sqrt{K_a}$

- If soil has a cohesion component, the active earth pressure is reduced by $2c\sqrt{K_a}$.

- $0 = \sigma_v K_a - 2c\sqrt{K_a}$

  $\sigma_v K_a = 2c\sqrt{K_a}$ or $\gamma z_o K_a = 2c\sqrt{K_a}$

  or $z_o = \dfrac{2c}{\gamma\sqrt{K_a}}$

- Thus, if the soil has a cohesion component, the active earth pressure up to a depth of $2c/\gamma\sqrt{K_a}$ is zero.

- Water infiltration in a tension crack results in additional hydrostatic pressure and therefore increased bending moments.

STUDENT EXERCISE 5

From Station 3+60 to 4+00, the subsurface conditions are same as in Student Exercise 3. However a 1 m wide strip load of 40 kPa located 1 m behind the wall as shown in Figure S5-1.

(a) Compute the lateral pressure due to the strip load at a depth of 3 m.

(b) Plot the variation of lateral pressure with depth due to the effect of strip load only.

(c) Plot all lateral pressures with depth.

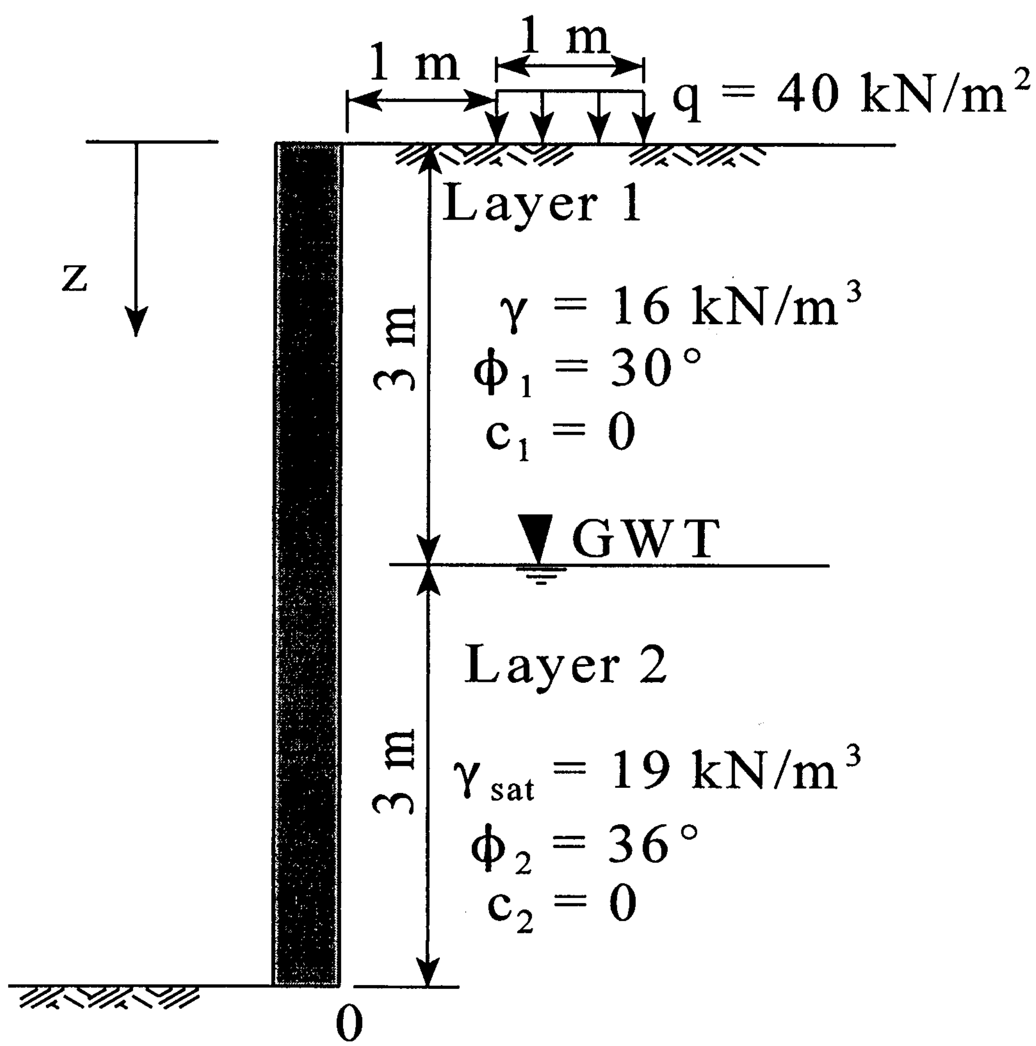
(d) Construct a design lateral pressure diagram.

Manual Reference:

Sections 2.4, 2.5 and 2-6; Eq. 2-5;

Figures 2-3, 2-7, 2-8 and 2-10.

Student Exercise 5 — Figure S5-1



Solution to Student Exercise 5

(a) ***From Figure 2-10***

$$p_h = \frac{2q}{\pi}(\beta - \sin\beta \cos 2\alpha)$$

Compute β and α at a depth of 3 m (see Figure S5-2)

$$\beta = \tan^{-1}\left(\frac{2}{3}\right) - \tan^{-1}\left(\frac{1}{3}\right)$$

$$\beta = 0.588 - 0.322$$

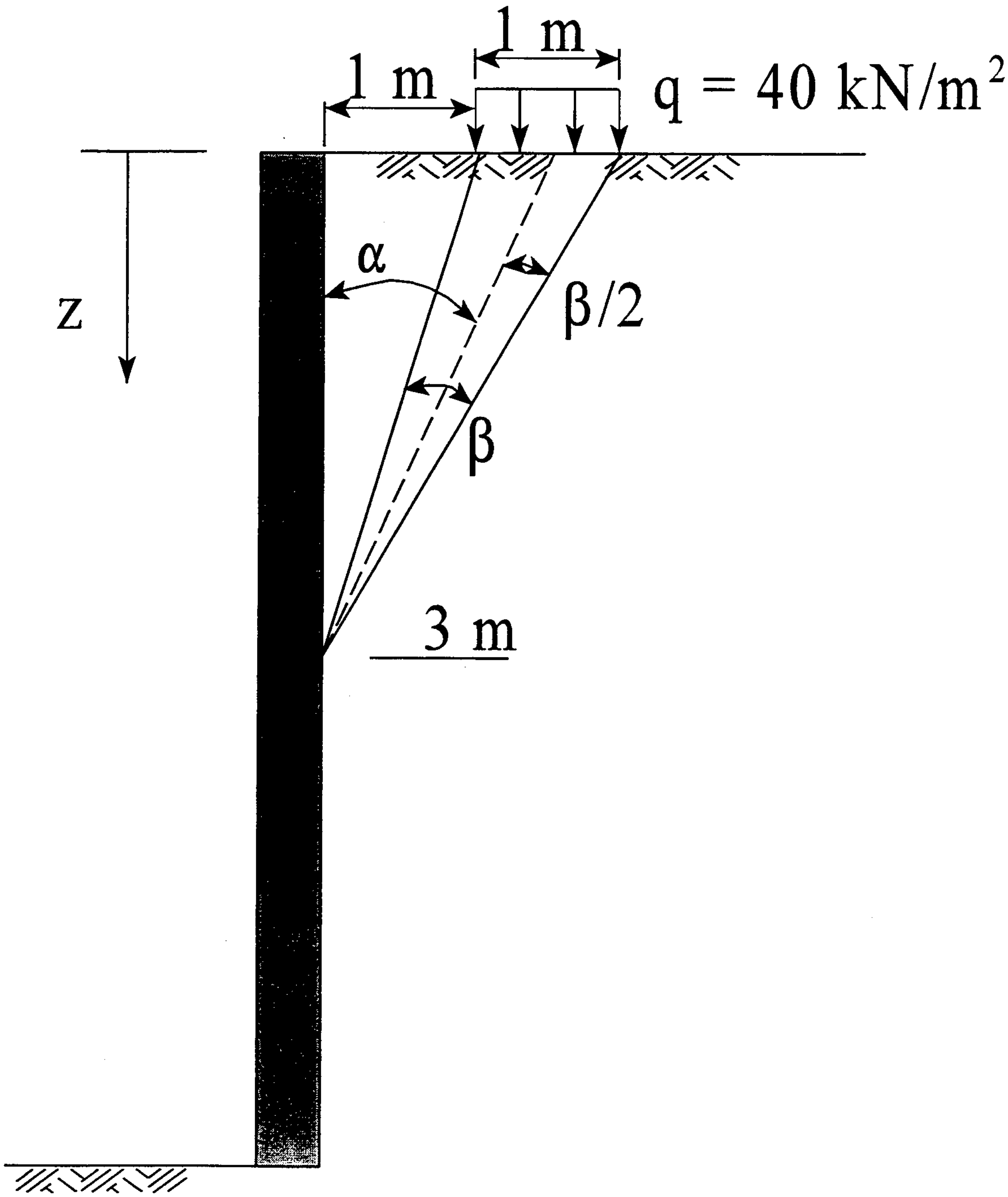
$$\beta = 0.266 \quad \text{Radians}$$

$$\alpha = \tan^{-1}\left(\frac{1}{3}\right) + \frac{\beta}{2}$$

$$\alpha = 0.322 + \frac{0.266}{2}$$

$$\alpha = 0.455 \quad \text{Radians}$$

Student Exercise 5
Figure S5-2



$$p_h = \frac{2(40)}{\pi}\left[0.266 - \sin(0.266)\cos\{2(0.455)\}\right]$$

$$p_h = 2.67 \text{ kPa}$$

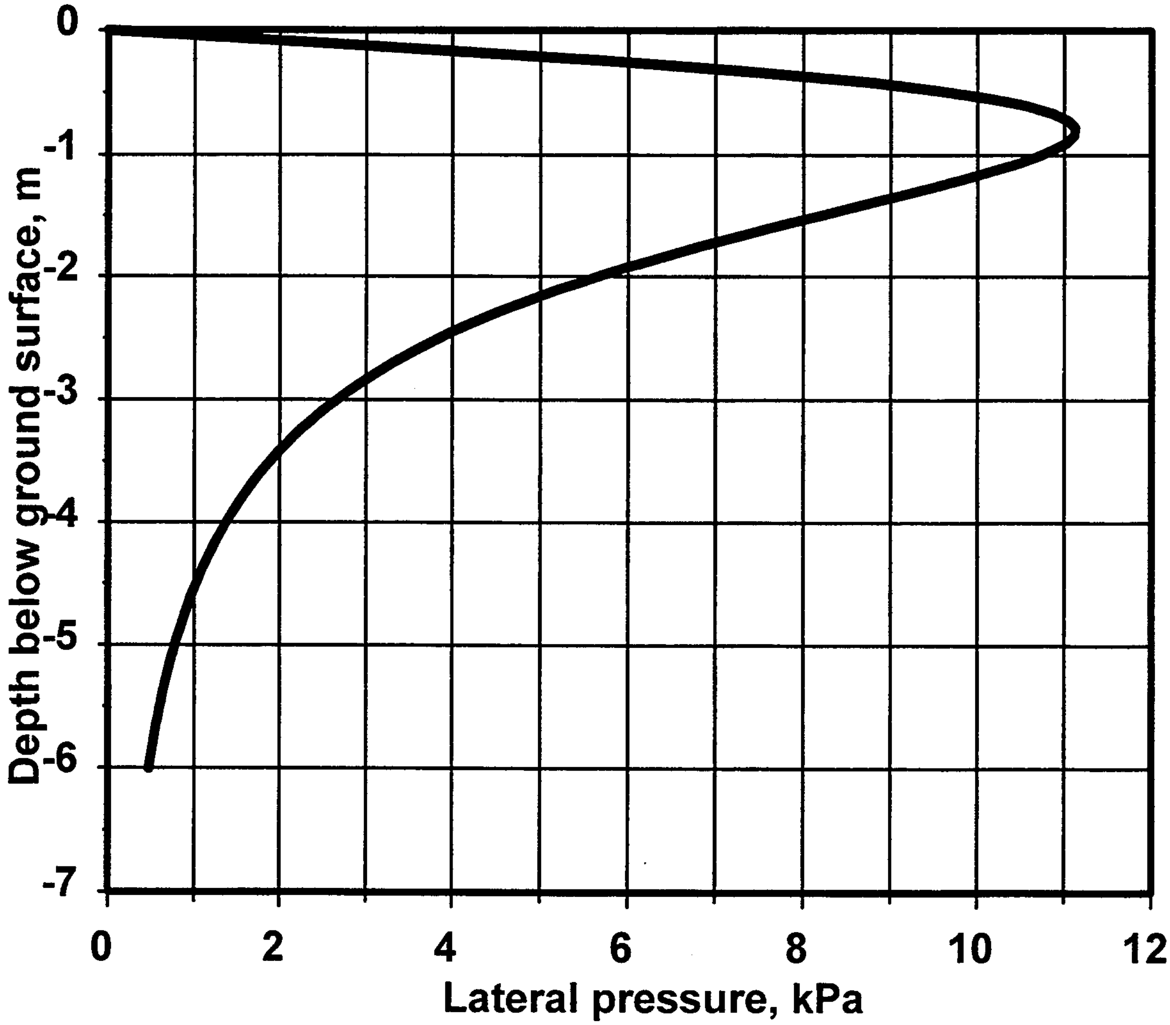
(b) Repeat computations at other depths and construct the variation of lateral pressure due to the strip load with depth as shown in Figure S5-3.

(c) Figure S5-4 shows a plot of all lateral pressures with depth.

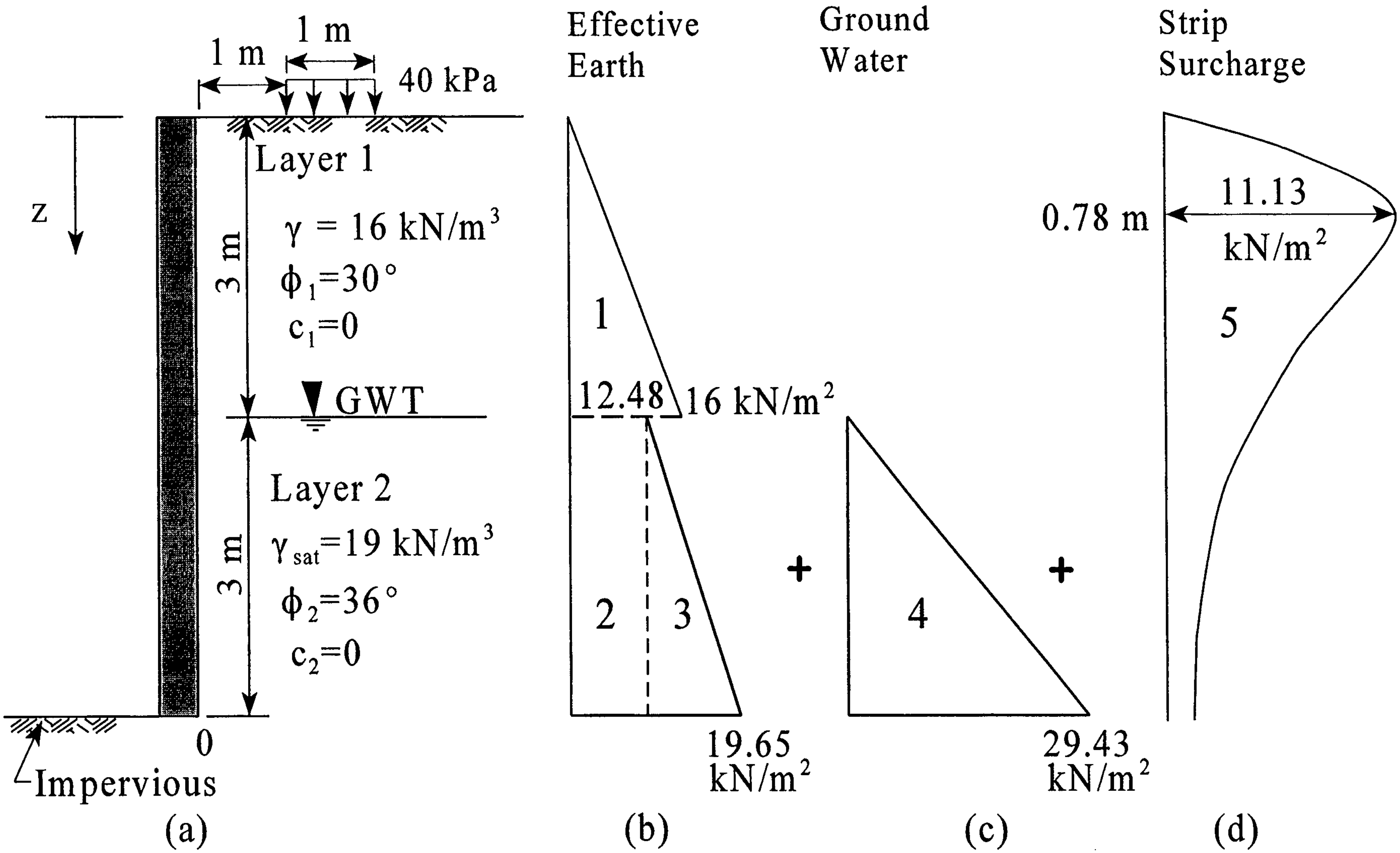
(d) Figure S5-5 shows the variation of total lateral pressures with depth.

Figure S5-6 shows the variation of the total lateral earth pressures and water pressure with depth. This is the preferred represtentation since water pressure is a definite quantity which can be accurately determined and has a known triangular distribution.

Student Exerise 5
Figure S5-3

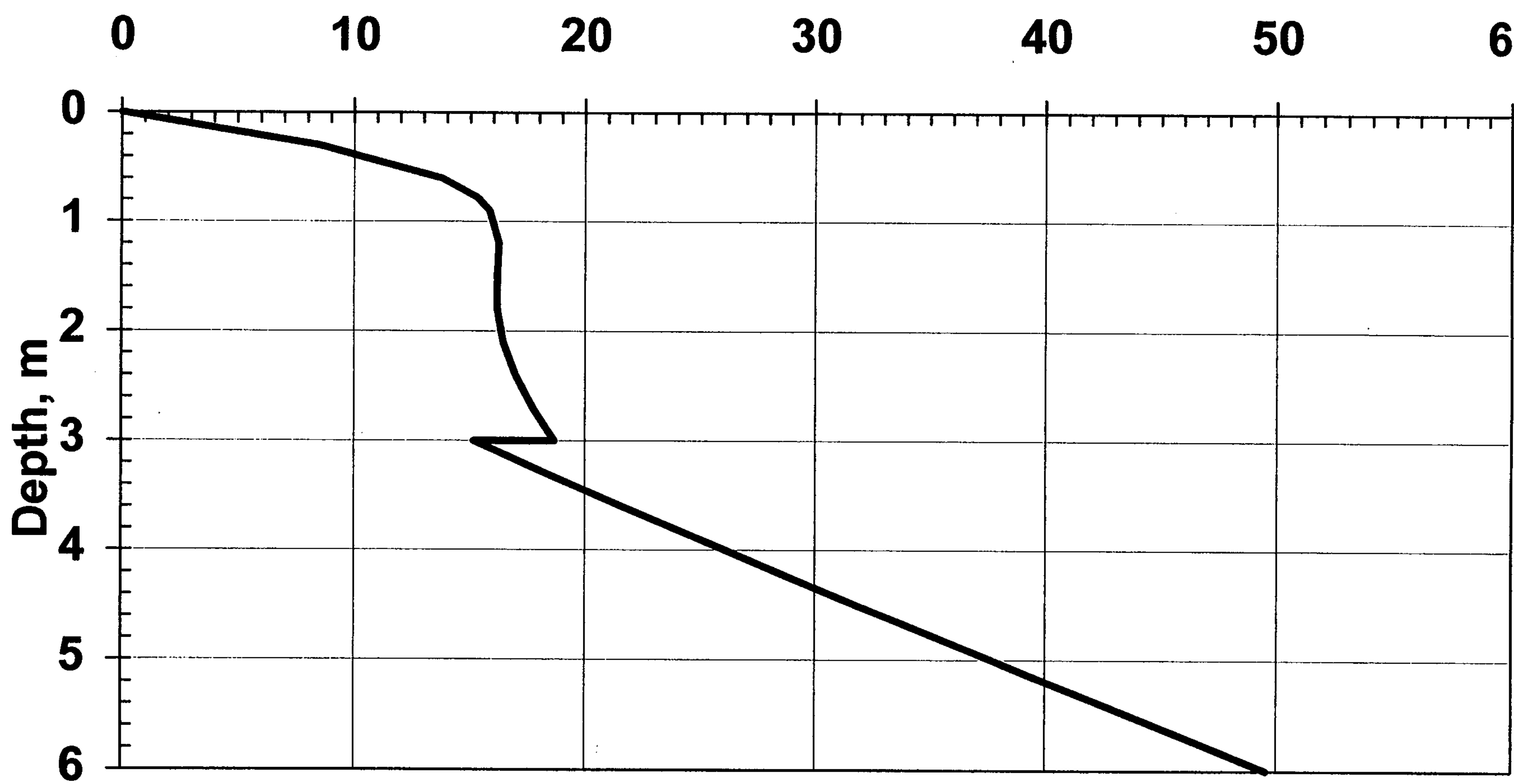


Student Exercise 5 Figure S5-4



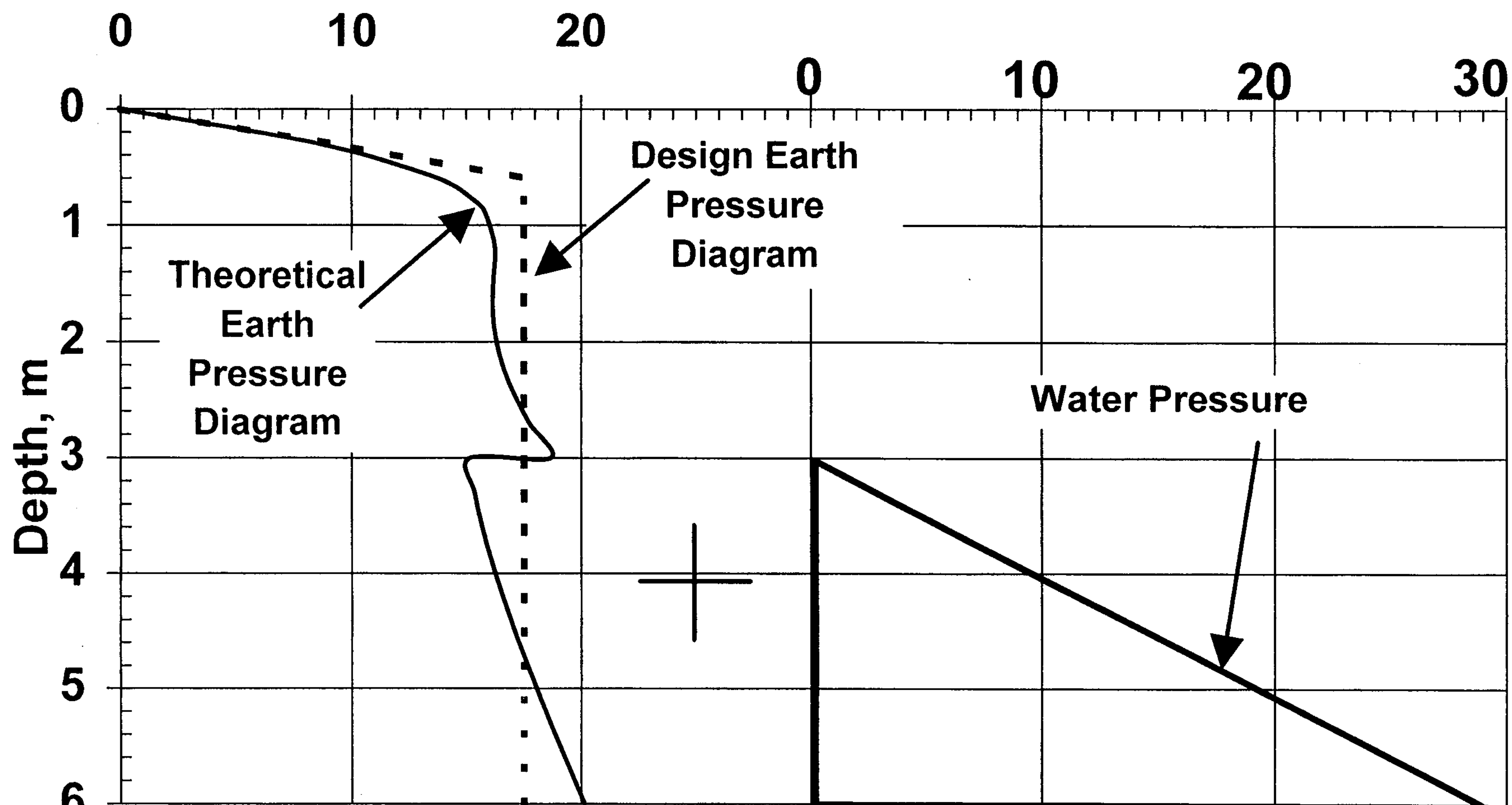
Student Exercise 5 *Figure S5-5*

WATER PRESSURE INCLUDED



Student Exercise 5 Figure S5-6

WATER PRESSURE SEPARATE



Key Points

- Be careful about angles while using elastic solutions for computation of earth pressures due to surcharges.

- Combine all lateral earth pressure diagrams into one diagram. Keep the lateral pressure diagram due to water separate.

- Develop a simplified earth pressure diagram for structural design.

- The simplified diagram should not be an envelope but an equivalent pressure diagram.

STUDENT EXERCISE 6

From Station 4+00 to 4+35, the proposed cross-section of the highway is shown in Figure S6-1.

The properties of the soils behind wall CD, based on laboratory tests, are shown in Figure S6-2.

For the wall CD:

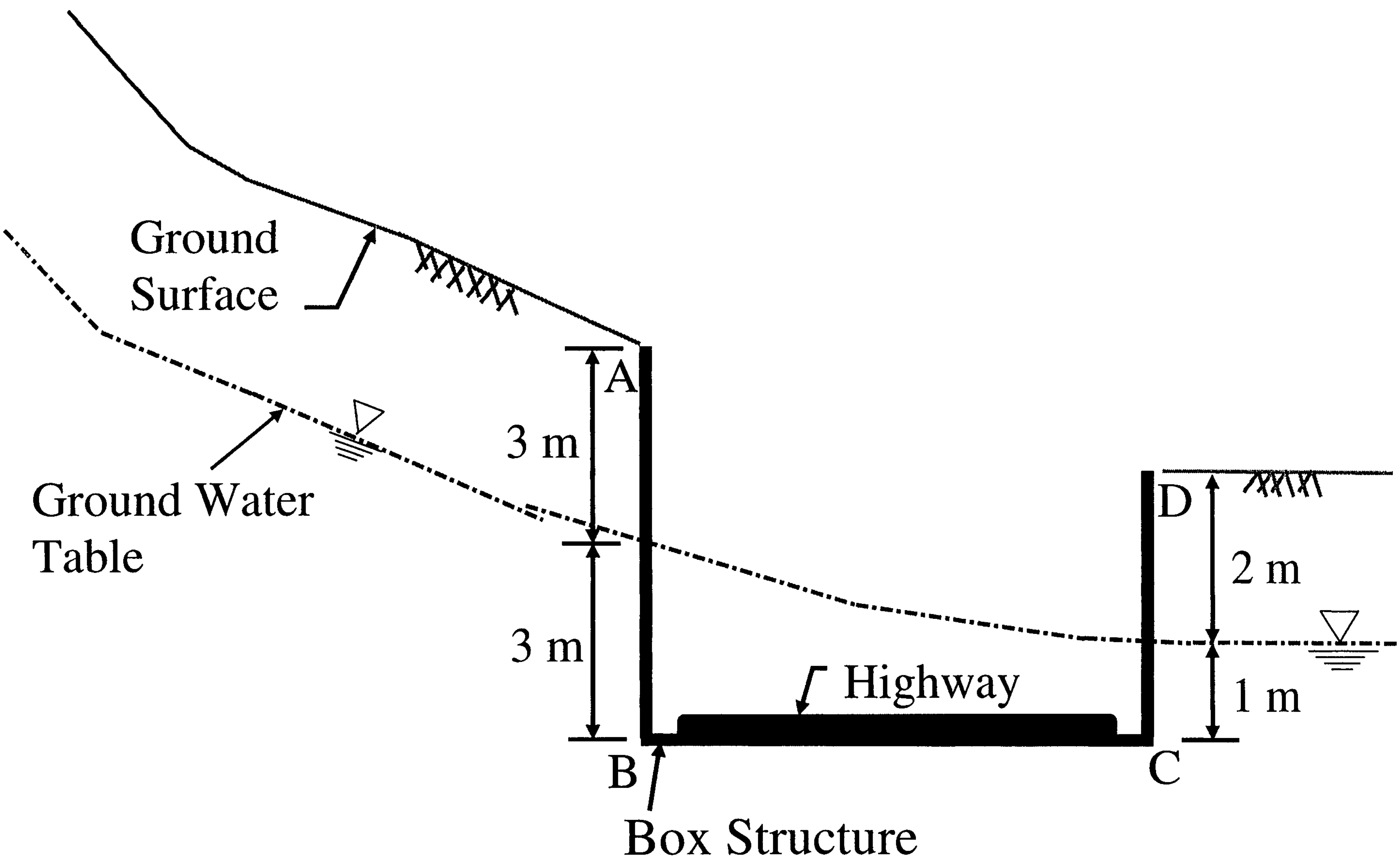
(a) Construct the passive pressure diagram

(b) Compute the lateral pressure diagram due to the surcharge.

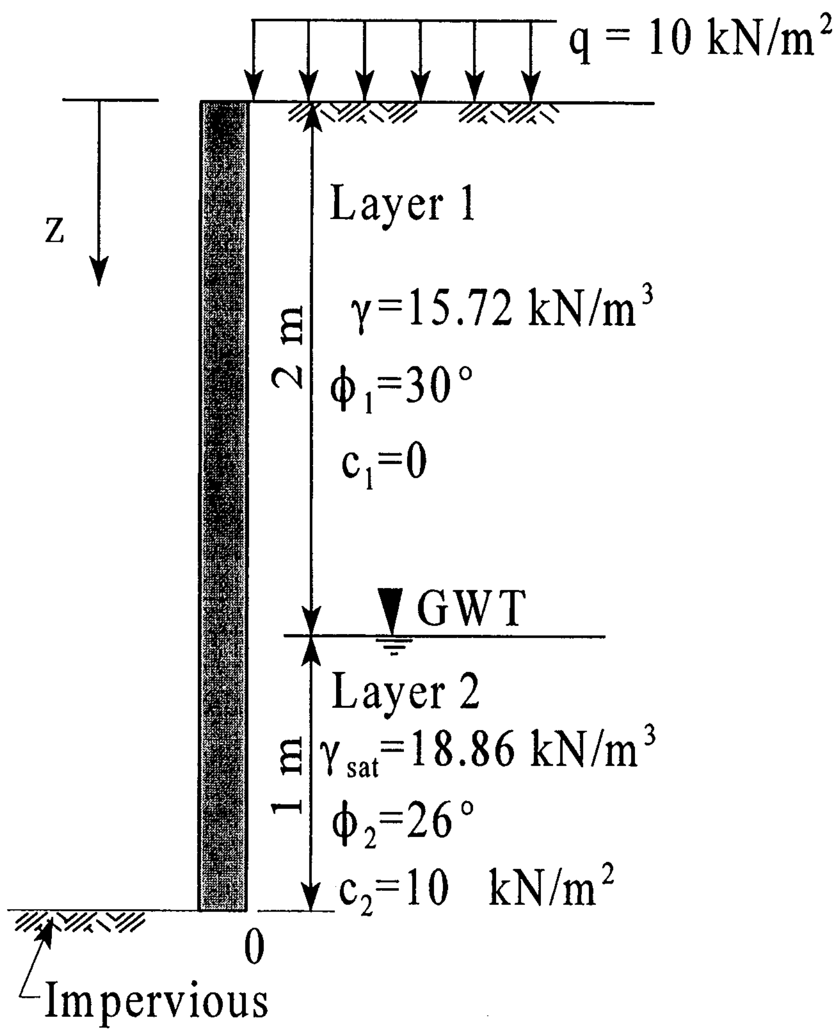
Manual Reference:

Sections 2.4, 2.5 and 2.6;
Eq. 2-6;
Figures 2-3e, 2-7, 2-8 and 2-10.

Student Exercise 6 Figure S6-1



Student Exercise 6 Figure S6-2



Solution to Student Exercise 6

Compute K_p ***(Eq. 2-6)***

$$K_{p1} = \tan^2 (45^\circ + 30^\circ/2) = 3$$

$$K_{p2} = \tan^2 (45^\circ + 26^\circ/2) = 2.56$$

Compute lateral pressures ***(Figure 2-3e)***

$$p_p = \sigma'_{vo} K_p + 2c\sqrt{K_p}$$

where σ'_{vo} = effective vertical (overburden) stress

σ'_{vo} is computed using effective unit weight γ'

$$\gamma' = \gamma_{sat} - \gamma_w$$

Effective Lateral Earth Pressures

z, m	σ'_{vo}, kN/m^2	Lateral pressure, p_p, kN/m^2
0	0	0
2^-	(15.72)(2) = 31.44	$31.44\,K_{p1} + (2)(0)\sqrt{K_{p1}} = 94.32$
2^+	(15.72)(2) = 31.44	$31.44\,K_{p2} + (2)(10)\sqrt{K_{p2}} = 112.49$
3	31.44+ (18.86-9.81)1 = 40.49	$40.49\,K_{p2} + (2)(10)\sqrt{K_{p2}} = 135.65$

Hydrostatic Pressure, p_w

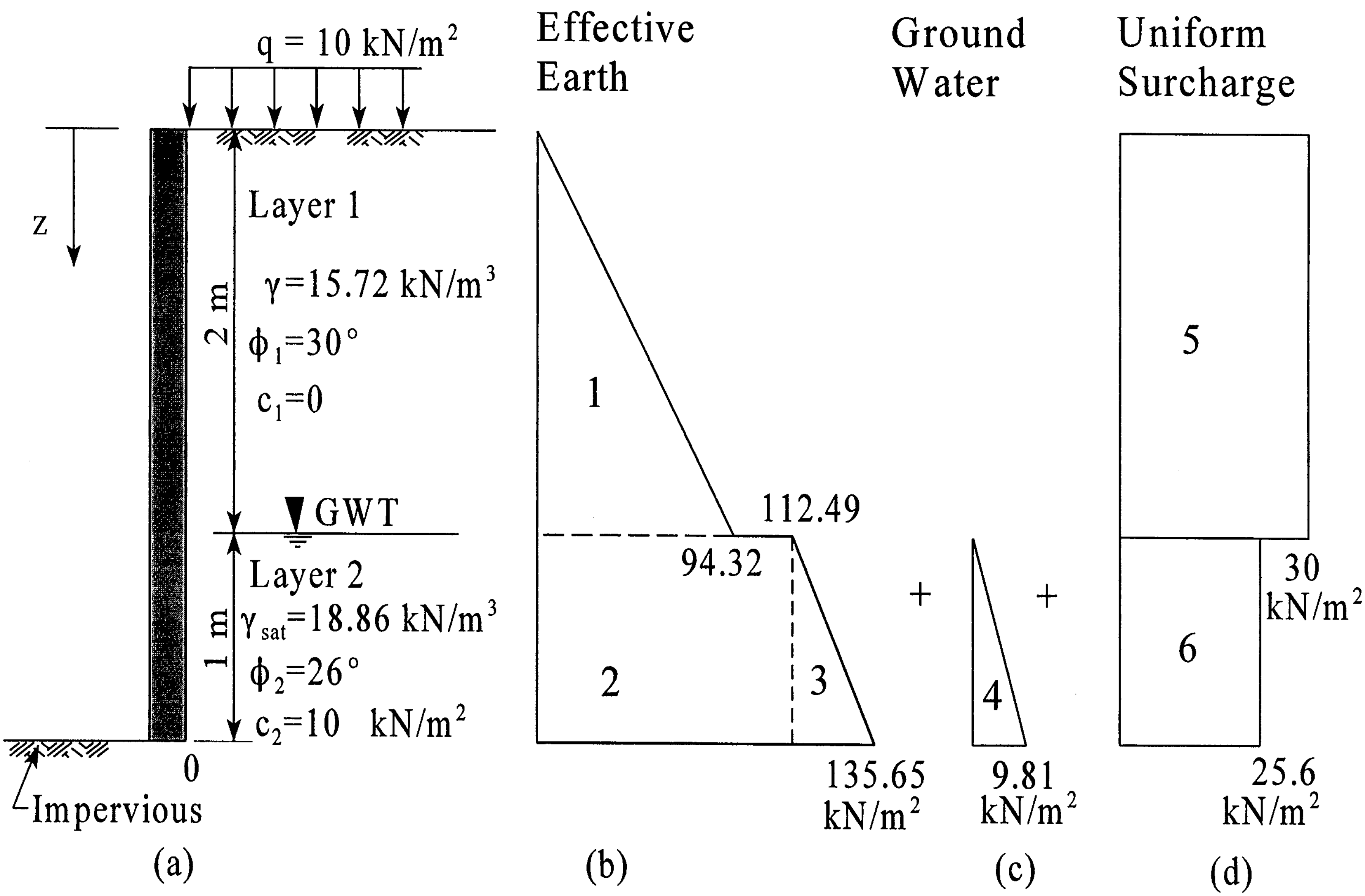
z, m	z_w, m	$\sigma_w = z_w \gamma_w$, kN/m^2	Lateral pressure, p_w, kN/m^2
0	0	0	0
2	0	0	0
3	1	1 (9.81)= 9.81	$K_w \sigma_w$ = 1.0(9.81) = 9.81

Lateral Pressure due to Surcharge Load

z, m	Lateral pressure, p_h, kN/m^2				
0	$K_{p1}\,q$	=	3 (10)	=	30
2^-	$K_{p1}\,q$	=	3 (10)	=	30
2^+	$K_{p2}\,q$	=	2.56(10)	=	25.6
3	$K_{p2}\,q$	=	2.56 (10)	=	25.6

Figure S6-3 shows the variation of all lateral pressures with depth.

Student Exercise 6 Figure S6-3



Total force per unit length of the wall is equal to the area of the pressure diagram

$$
\begin{aligned}
P_h &= P_1 + P_2 + P_3 + P_4 + P_5 + P_6 \\
&= \text{Area 1} + \text{Area 2} + \text{Area 3} + \text{Area 4} \\
&\qquad + \text{Area 5} + \text{Area 6} \\
&= \tfrac{1}{2}(2)(94.32) + (112.49)(1) \\
&\qquad + \tfrac{1}{2}(135.65 - 112.49)(1) + \tfrac{1}{2}(1)(9.81) \\
&\qquad + (30)(2) + (25.6)(1) \\
&= 94.32 + 112.49 + 11.58 + 4.905 \\
&\qquad + 60 + 25.6 \\
&= \mathbf{308.9\ kN/m}
\end{aligned}
$$

Key Points

- $p_a = \sigma_v K_a + 2c\sqrt{K_a}$

- If soil has a cohesion component, the passive earth pressure is increase by $2c\sqrt{K_a}$.

STUDENT EXERCISE 7

At Station 5+350 to 5+550, a line load of 10 kN/m is located 1 m behind the top of a 6 m high wall as shown in Figure S7-1.

(a) Compute the lateral pressure at a depth of 3 m.

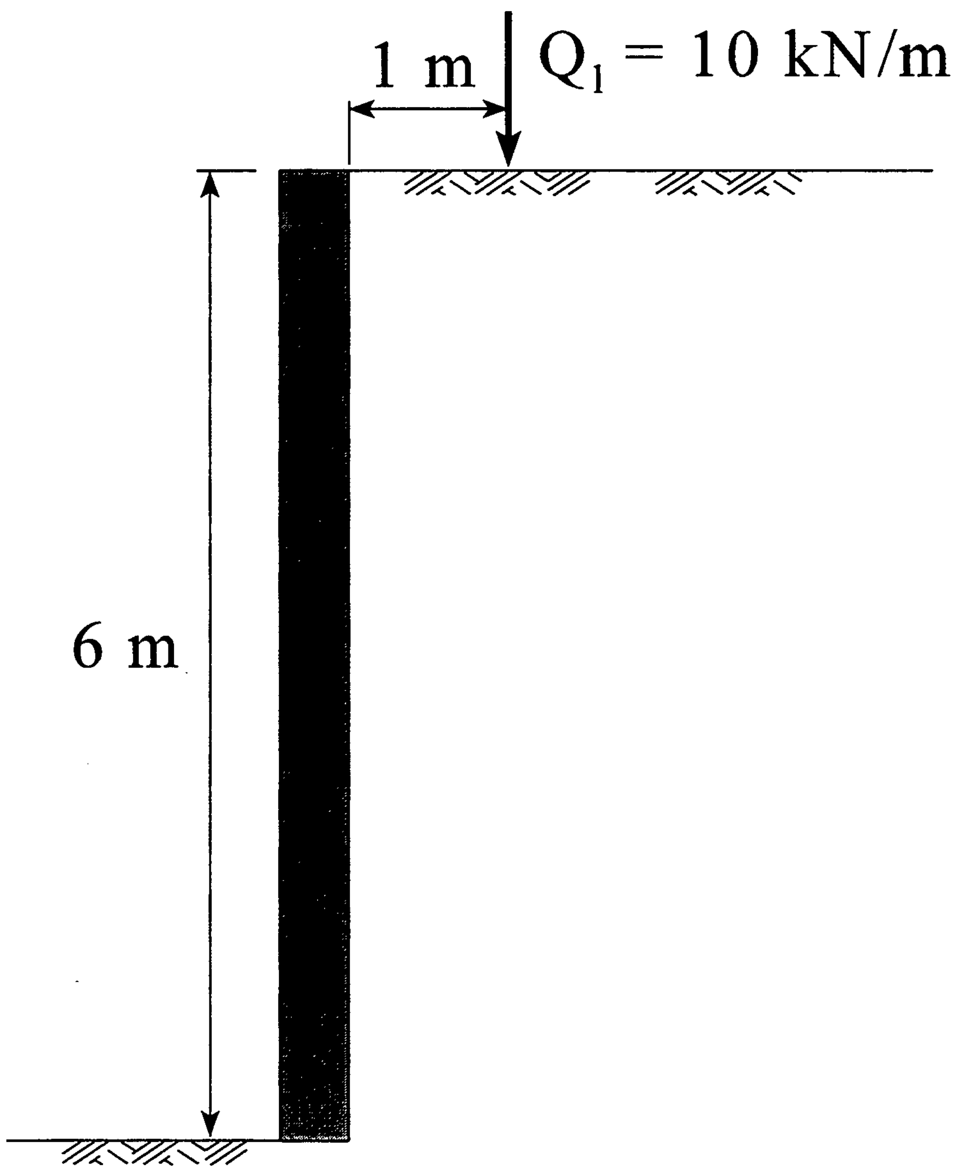
(b) Construct the lateral pressure diagram.

(c) Compute resultant load and the depth at which it acts.

Manual Reference:

Section 2.6; Figure 2-10.
Example Problem on Page 2-17,18

Student Exercise 7
Figure S7-1



Solution to Student Exercise 7

From Figure 2-10

$\bar{m} \;=\; 1/6 = 0.167 < 0.4$

Hence the lateral pressure is given by:

$$p_h = 0.20 \left(\frac{Q_l}{H} \right) \left[\frac{\bar{n}}{\left(0.16 + \bar{n}^2\right)^2} \right]$$

For $z = 3$ m $\quad \bar{n} = z/H = 3/6 = 0.5$

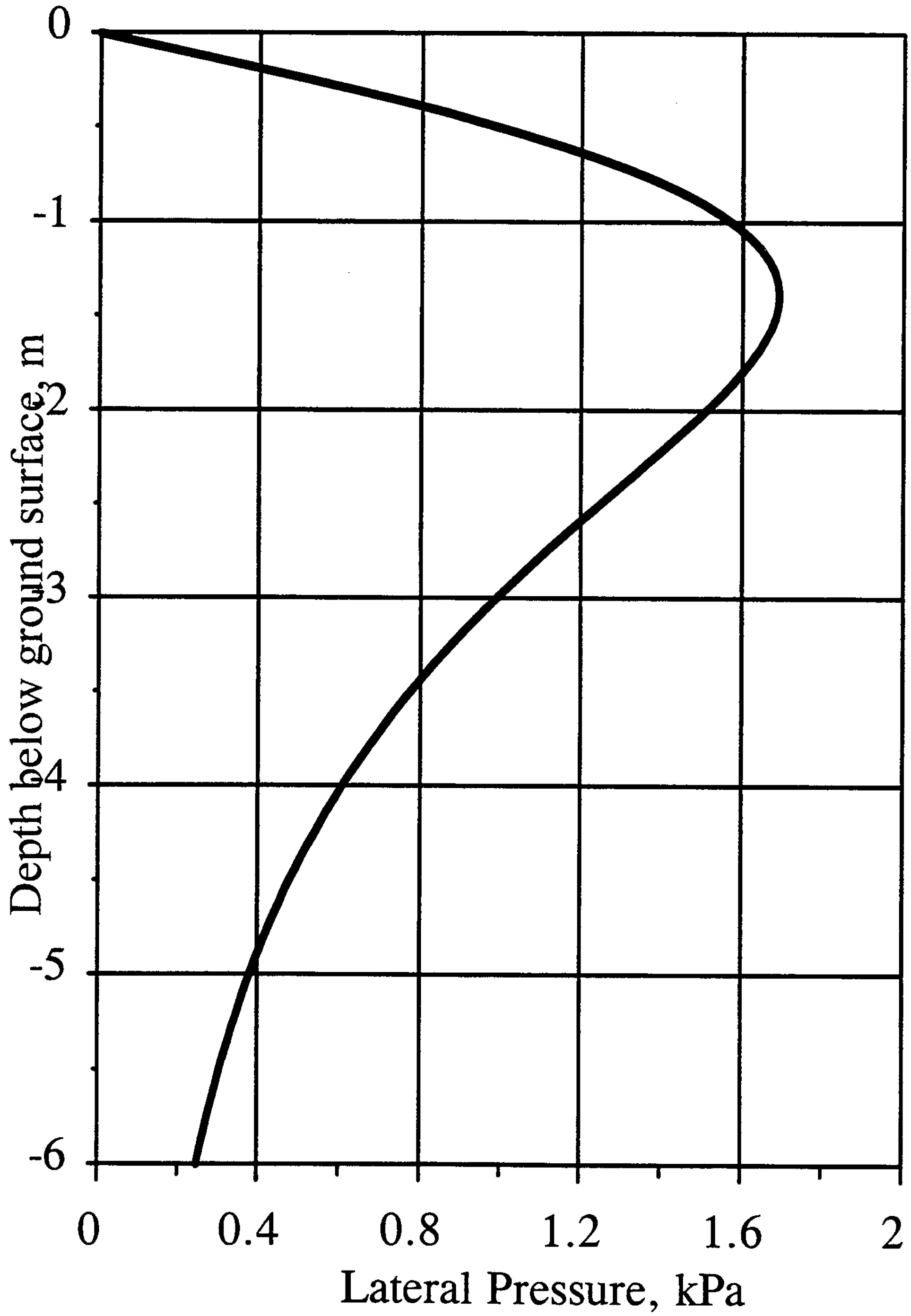
Substituting values:

$$p_h = 0.20 \left(\frac{10 \text{ kN/m}}{6 \text{ m}} \right) \left[\frac{0.5}{\left(0.16 + 0.5^2\right)^2} \right]$$

$p_h = 0.99$ kPa

Repeat computations at other depths and construct the variation of lateral pressure due to the line load with depth as shown in Figure S7-2.

Student Exercise 7
Figure S7-2



Resultant Load, P_h

P_h $=0.55\ Q_l$

$=0.55\ (10\ kN/m)$

$=5.5\ kN/m$

P_h acts at $0.6H=3.6$ m from bottom of wall

Key Points

- The equations to compute lateral pressures are different for values of $\overline{m} > 0.4$ and $\overline{m} < 0.4$.

STUDENT EXERCISE 8

From Station 5+850 to 6+50, a fill wall is needed to maintain the grade of the highway. A cantilever reinforced cast-in-place wall shown in Figure S8-1 was selected. For this wall, compute the following:

(a) Factor of safety against sliding, FS_S. Neglect passive resistance in front of the wall. Assume friction angle between concrete and foundation soil as $\delta_b = (3/4)\phi_b$.

(b) Factor of safety against overturning, FS_O

(c) Eccentricity of the resultant force, e

(d) Factor of safety against bearing capacity failure, FS_{BC}

Modify the wall as necessary to meet the following limiting criteria.

$FS_S \geq 1.5$ $\quad$ $FS_O \geq 2.0$ $\quad$ $e \leq L/6$ $\quad$ $FS_{BC} \geq 3.0$

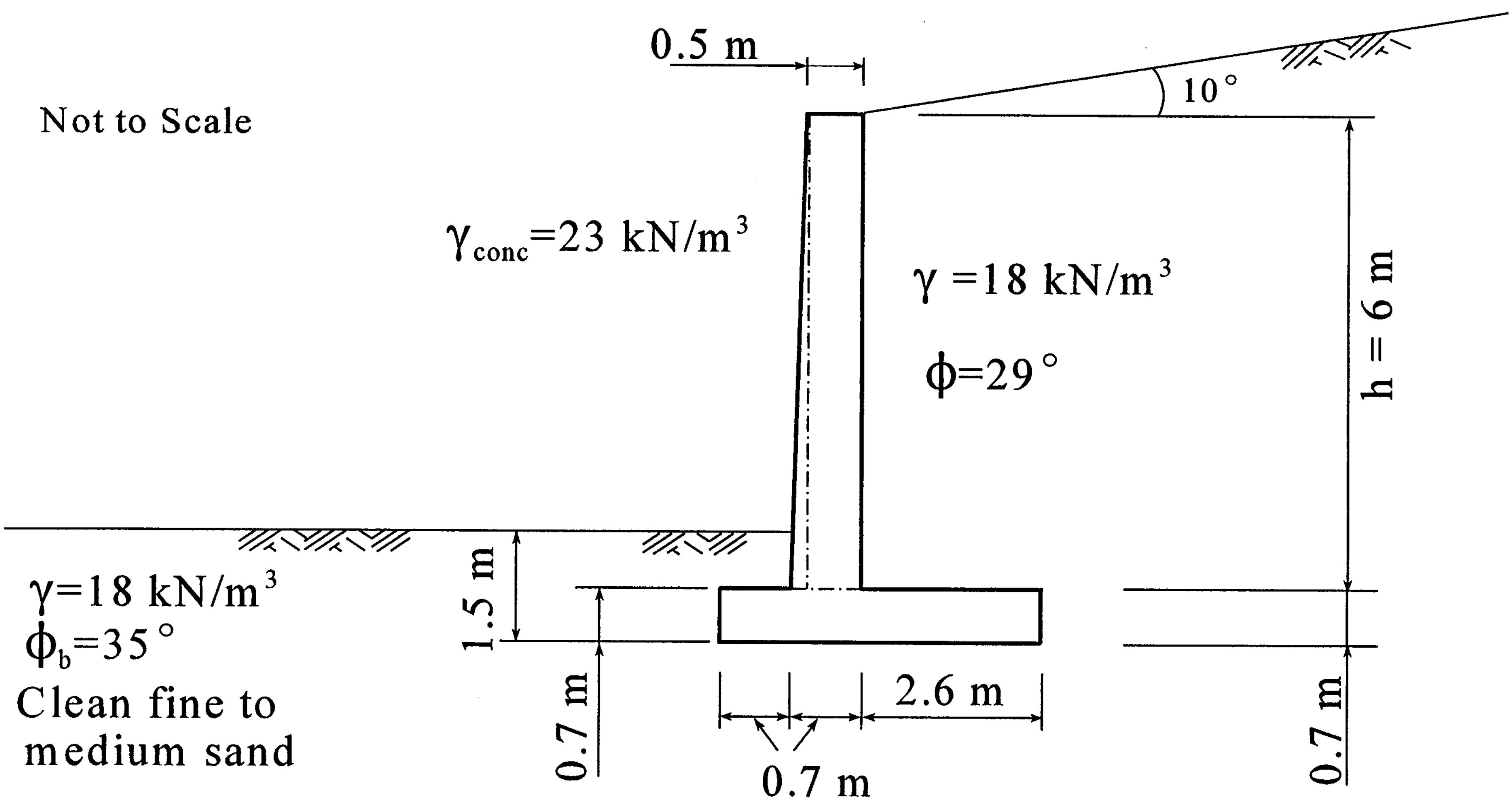
The ultimate bearing capacity of foundation soil is 900 kPa.

Manual Reference:

Figures 2-2, 4-6 and 4-7

Example Problem 4-1 in Chapter 4

Student Exercise 8   Figure S8-1



Solution to Student Exercise 8

Compute total height of soil exerting pressure (Refer Figure S8-2):

$H \quad = 0.7 \text{ m} + 6.0 \text{ m} + \Delta h \text{ m}$

$H \quad = 0.7 \text{ m} + 6.0 \text{ m} + 2.6 \text{ m} \tan 10°$

$\quad = 7.16 \text{ m}$

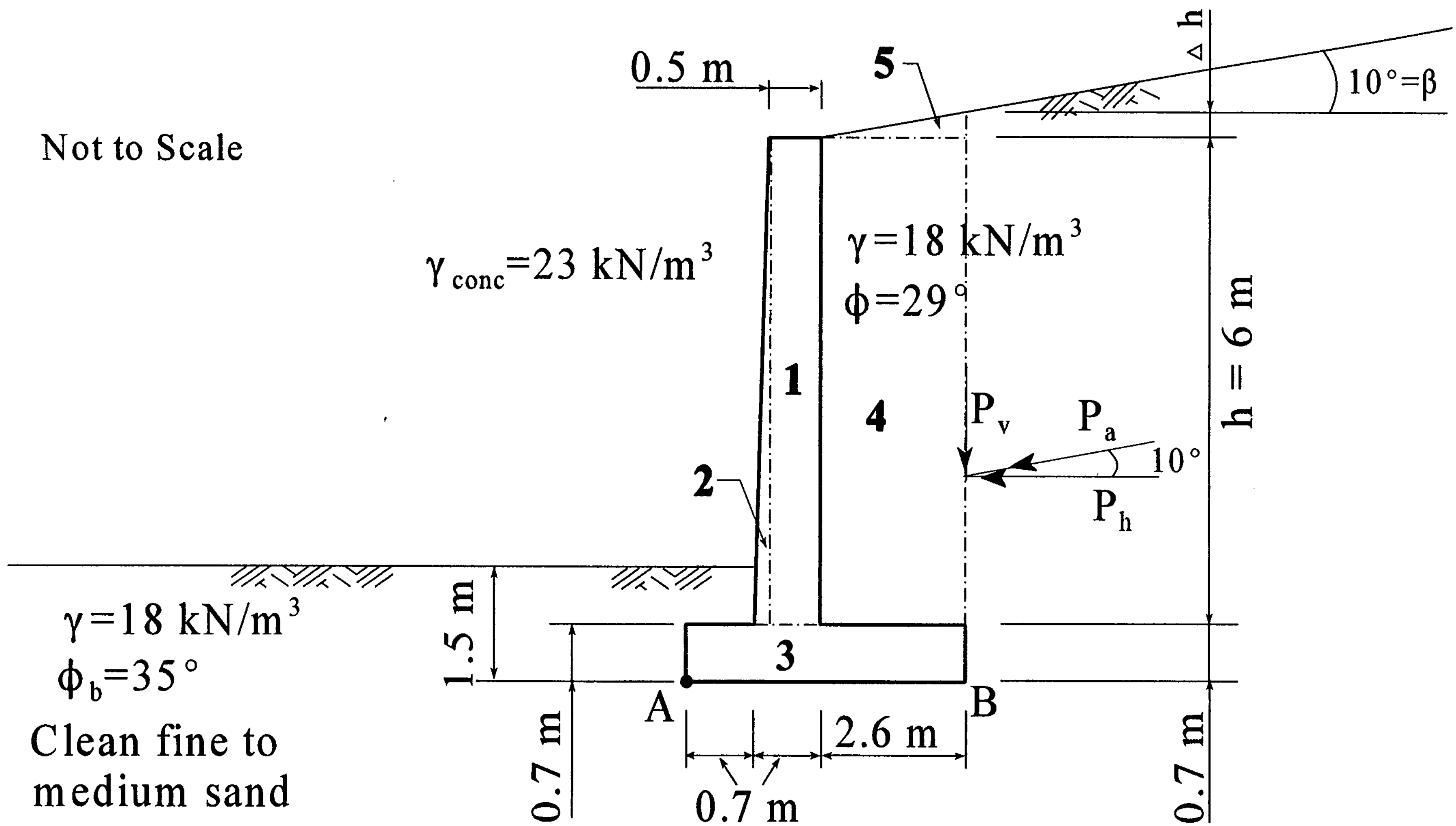
Compute K_a : ***(Figure 2-2)***

$$K_a = \frac{\cos^2\phi}{\cos\delta\left[1 + \sqrt{\dfrac{\sin(\phi+\delta)\sin(\phi-\beta)}{\cos\delta\cos(-\beta)}}\right]^2}$$

where:
ϕ = Internal friction angle of soil = 29°
β = Angle of backfill with horizontal = 10°
δ = Angle of backfill with horizontal = β = 10°

Substituting values, we obtain:

Student Exercise 8 Figure S8-2



$$K_a = \frac{\cos^2 29^\circ}{\cos 10^\circ \left[1 + \sqrt{\dfrac{\sin(29^\circ + 10^\circ)\sin(29^\circ - 10^\circ)}{\cos 10^\circ \cos(-10^\circ)}}\right]^2}$$

$K_a = 0.365$

Compute resultant of active pressure, P_a

$$\begin{aligned} P_a &= \tfrac{1}{2}\gamma K_a H^2 \\ &= \tfrac{1}{2}(18\ \text{kN/m}^3)(0.365)(7.16\ \text{m})^2 \\ &= 168.41\ \text{kN/m} \end{aligned}$$

Resolve P_a into horizontal and vertical components:

$$\begin{aligned} P_h &= P_a \cos\beta \\ &= 168.41\ \text{kN/m} \cos 10^\circ \\ &= 165.85\ \text{kN/m} \end{aligned} \qquad \begin{aligned} P_v &= P_a \sin\beta \\ &= 168.41\ \text{kN/m} \sin 10^\circ \\ &= 29.24\ \text{kN/m} \end{aligned}$$

Moment arm of P_h about A, $b = H/3 = 7.16/3 = 2.39$ m

Moment arm of P_v about A, $g = B = 4$ m

	Weight, kN/m (m) (m) (kN/m^3)=kN/m	Moment arm about A, m	Moment about A, (kN/m).m = kN.m/m
1	(0.5)(6)(23) = 69.0	0.7+0.2+(0.5/2) = 1.15	(69)(1.15) = 79.35
2	(0.5)(0.2)(6)(23) = 13.8	0.7+(2/3) (0.2) = 0.83	(13.8)(0.83) = 11.45
3	(4)(0.7)(23) = 64.4	4/2 = 2.00	(64.4)(2.0) = 128.80
4	(2.6)(6)(18) = 280.8	0.7+0.7+(2.6/2) = 2.70	(280.8)(2.7) = 758.16
5	(0.5)(2.6)(0.46)(18) = 10.8	0.7+0.7+(2/3)(2.6) = 3.13	(10.8)(3.13) = 33.69
	W = 438.8 kN/m		M_w=W.a = 1011.45 kN.m/m

Sliding

$$FS_s = \frac{(W + P_v)\tan\delta_b}{P_h}$$ ***(Figure 4-6)***

where:

W = Weight of concrete and soil on $\overline{AB}$

δ_b = Friction angle between concrete and foundation soil

= $(3/4)\ \phi_b = (3/4)\ (35) = 26.25°$

Substituting values:

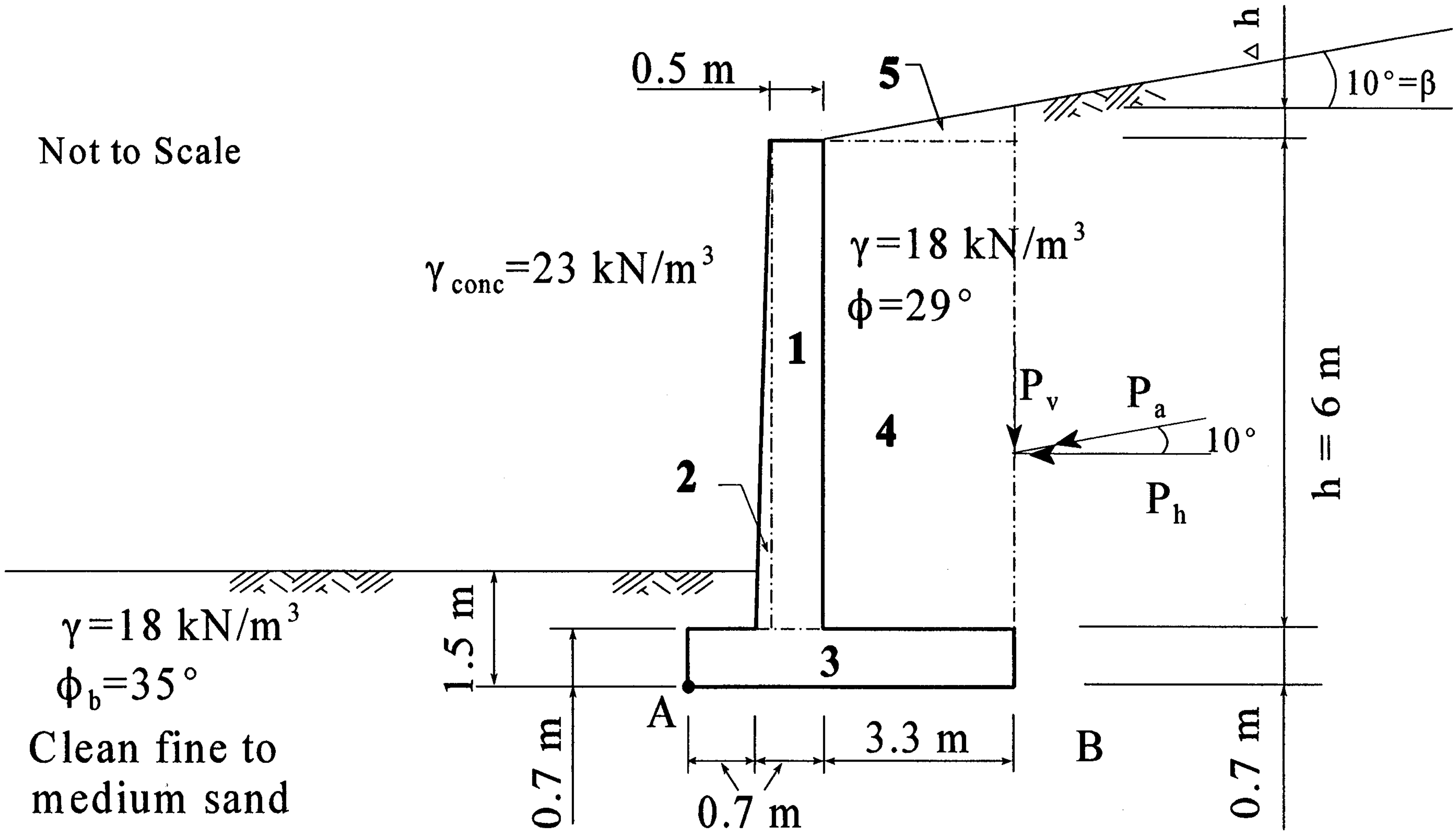
$$FS_s = \frac{(438.8 \text{ kN/m} + 29.24 \text{ kN/m})\tan 26.25°}{165.85 \text{ kN/m}}$$

$$FS_s = \frac{230.89 \text{ kN/m}}{165.85 \text{ kN/m}} = 1.39 < 1.50$$

Increase the width of heel or provide a shear key

Try a heel width of 3.3 m (Figure S8-3)

Student Exercise 8 Figure S8-3



Compute total height of soil exerting pressure:

$$H = 0.7\text{ m} + 6.0\text{ m} + 3.3\text{ m}\ \tan 10^\circ$$

$$= 7.28\text{ m}$$

Compute resultant of active pressure, P_a

$$P_a = \tfrac{1}{2}\gamma K_a H^2$$
$$= \tfrac{1}{2}(18\text{ kN/m}^3)(0.365)(7.28\text{ m})^2$$
$$= 174.10\text{ kN/m}$$

Resolve P_a into horizontal and vertical components:

$$P_h = P_a \cos\beta \qquad P_v = P_a \sin\beta$$
$$= 174.10\text{ kN/m}\cos 10^\circ \qquad = 174.10\text{ kN/m}\sin 10^\circ$$
$$= 171.45\text{ kN/m} \qquad = 30.23\text{ kN/m}$$

Moment arm of P_h about A, $b = H/3 = 7.28\text{ m}/3 = 2.43\text{m}$

Moment arm of P_v about A, $g = B = 4.7\text{ m}$

	Weight, kN/m (m) (m) (kN/m^3)=kN/m	Moment arm about A, m	Moment about A, (kN/m).m=kN·m/m
1	(0.5)(6)(23) = 69.0	0.7+0.2+(0.5/2) = 1.15	(69)(1.15) = 79.35
2	(0.5)(0.2)(6)(23) = 13.8	0.7+(2/3) (0.2) = 0.83	(13.8)(0.83) = 11.45
3	(4.7)(0.7)(23) = 75.7	4.7/2 = 2.35	(75.7)(2.35) = 177.90
4	(3.3)(6)(18) = 356.4	0.7+0.7+(3.3/2) = 3.05	(356.4)(3.05) = 1087.02
5	(0.5)(3.3)(0.58)(18) = 17.3	0.7+0.7+(2/3)(3.3) = 3.60	(17.3)(3.60) = 62.28
	W = 532.2		M_w = W.a = 1418.00

$$FS_s = \frac{(532.2\ kN/m + 30.23\ kN/m)\tan 26.25^{o}}{171.45\ kN/m} = \frac{277.36\ kN/m}{171.45\ kN/m} = 1.62 > 1.50\ \text{O.K.}$$

Overturning

From ***(Figure 4-6)***

$$FS_o = \frac{\Sigma M_R}{\Sigma M_o} = \frac{M_w}{M_{PH} - M_{PV}} = \frac{M_w}{P_h b - P_v g}$$

where:

ΣM_R = Sum of resisting moments about A = M_w

ΣM_o = Sum of overturning moments about A = $P_h b$ - $P_v g$

Substituting values:

$$FS_o = \frac{1418.0 \text{ kN.m/m}}{(171.45 \text{ kN/m})(2.43 \text{ m}) - (30.23 \text{ kN/m})(4.7 \text{ m})}$$

$$FS_o = \frac{1418.0 \text{ kN}}{274.54 \text{ kN}} = 5.16 > 2.0 \quad \text{O.K.}$$

Eccentricity (Location of Resultant)

Location of resultant at distance d from A is given by:
(Figure 4-6)

$$d = \frac{\Sigma M_R - \Sigma M_o}{\Sigma V} = \frac{W.a - P_h.b + P_v.g}{W + P_v}$$

$$d = \frac{1418.0\,kN.m/m - 416.62\,kN.m/m + 142.08\,kN.m/m}{532.2\,kN/m + 30.23\,kN/m}$$

$$d = \frac{1143.46\ kN.m/m}{562.43\ kN/m} = 2.03\ m$$

Eccentricity of load about center of base is given by:

$$e = \frac{B}{2} - d = \frac{4.7\ m}{2} - 2.03\ m = 0.32\ m$$

$$\frac{B}{6} = \frac{4.7\ m}{6} = 0.78\ m$$

$$e < \frac{B}{6} \qquad \text{O.K.}$$

Bearing Capacity

Compute the maximum and minimum pressures under the wall footing: ***(Figure 4-6)***

$$q_{max,min} = \frac{\Sigma V}{B}\left(1 \pm \frac{6e}{B}\right) = \frac{W + P_v}{B}\left(1 \pm \frac{6e}{B}\right)$$

$$q_{max,min} = \frac{532.2\,\text{kN/m} + 30.23\,\text{kN/m}}{4.7\,\text{m}}\left(1 \pm \frac{6(0.32\,\text{m})}{4\,\text{m}}\right)$$

$$q_{max,min} = 119.67\ \text{kN/m}^2\ (1.48\ \text{or}\ 0.52)$$

$q_{max} = 177.11\ \text{kN/m}^2$

$q_{min} = 62.23\ \text{kN/m}^2$

Given : $q_{ult} = 900\ \text{kN/m}^2$

$FS_{BC} = q_{ult}/q_{max}$

$= 900/177.11 = 5.08 > 3.0$ O.K.

Summary:

Factor of safety against sliding	FS_s	$= 1.62$
Factor of safety against overturning	FS_o	$= 5.16$
Eccentricity of Resultant	e	$= 0.32$ m
Factor of Safety Against Bearing Failure	FS_B	$= 5.08$

IMPORTANT

Check factor of safety against global failure using slope stability analysis from Module 3 (Soil Slopes and Embankments).

Shear Key Option

$$FS_s = \frac{(W + P_v)\tan\delta_b + P_p}{P_h}$$ *(Figure 4-7)*

where:

P_p = Passive resistance provided by shear key

From the computations for 2.6 m heel:

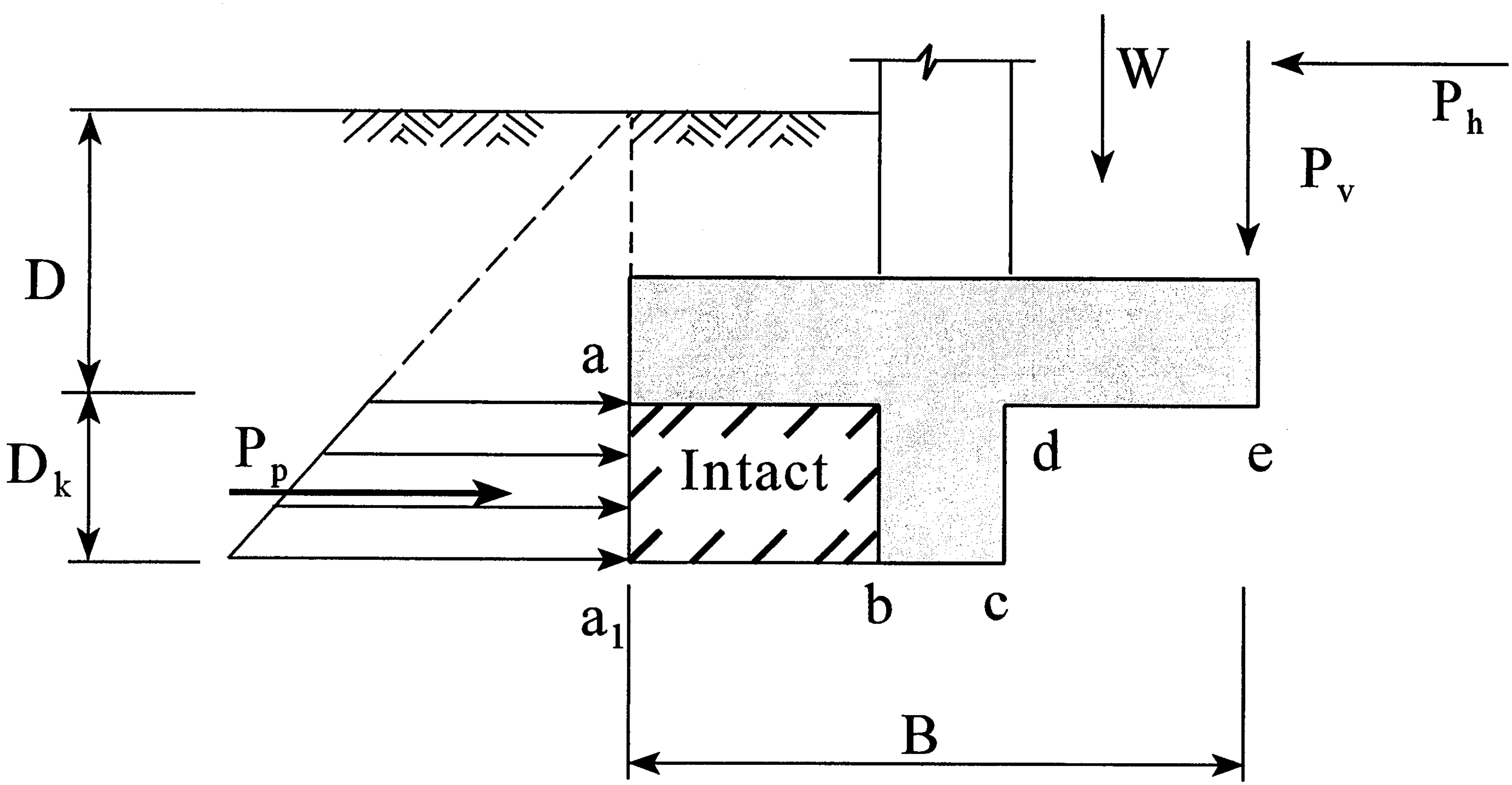
W	=	438.8 kN/m	P_v	=	29.24 kN/m
δ_b	=	26.25°	P_h	=	165.85 kN/m

Solve the equation of FS_s for P_p to achieve a value of 1.5

$$1.5 = \frac{(438.3\,kN/m + 29.24\,kN/m)\tan 26.25^\circ + P_p\,kN/m}{165.85\,kN/m}$$

$P_p \approx 18$ kN/m

Student Exercise 8 — Figure S8-4



$$P_p = \tfrac{1}{2}\,\gamma K_p\,(D + D_K)^2 - \tfrac{1}{2}\,\gamma K_p\,D^2$$

$$= \tfrac{1}{2}\,\gamma K_p\,(2D + D_K)\,D_K \qquad \text{(Eq. 1)}$$

$$K_p = \tan^2(45^\circ + \phi/2)$$

$$= \tan^2(45^\circ + 35^\circ/2)$$

$$= 3.69$$

Substitute $D = 1.5$ m, $\gamma = 18$ kN/m^3 and K_p in Equation 1

$$18 \text{ kN/m} = \tfrac{1}{2}\,(18 \text{ kN/m}^3)\,3.69\,\{(2)(1.5 \text{ m}) + D_K \text{m})\,D_K \text{ m}$$

Simplifying we get the following quadratic equation

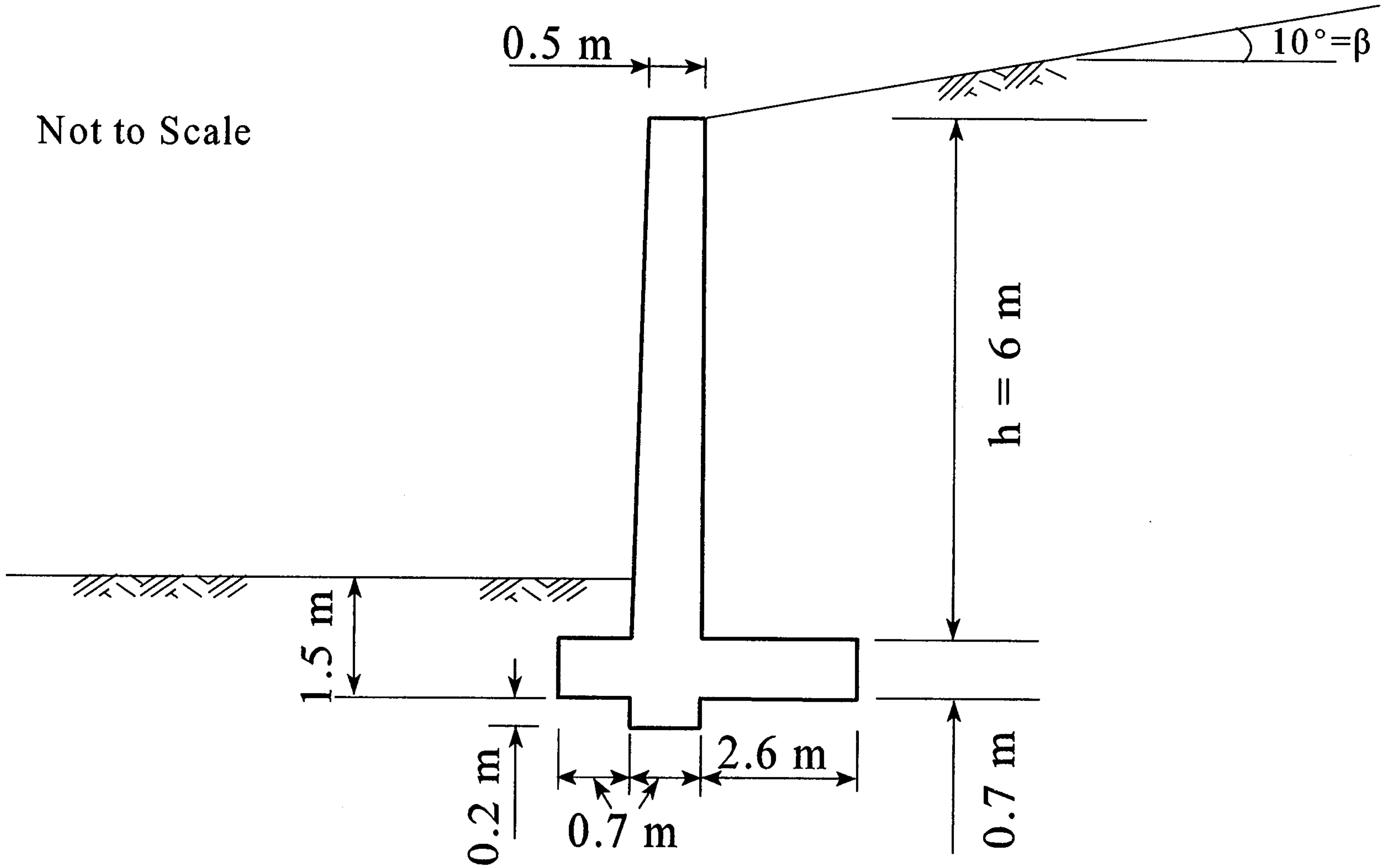
$$D_K^2 + 3D_k - 0.54 = 0$$

Solve the quadratic equation for depth of shear key, D_K

D_K = 0.17 m   Say 0.20 m

Student Exercise 8 — Figure S8-5

Not to Scale



STUDENT EXERCISE 9

The ground profile between 6+150 to 6+650 is shown in Figure S9-1. A 7 m high MSE wall was selected to retain the highway in this stretch. Consider that the traffic surcharge is equivalent to a uniform live load of 10 kPa, the unit weight of the retained fill is 20 kN/m^3, and the frictional strength of this fill and the foundation soil has been estimated at 30 degrees, with no cohesion.

Compute:

(a) A preliminary length of reinforcement

(b) The horizontal pressure on the reinforced fill volume

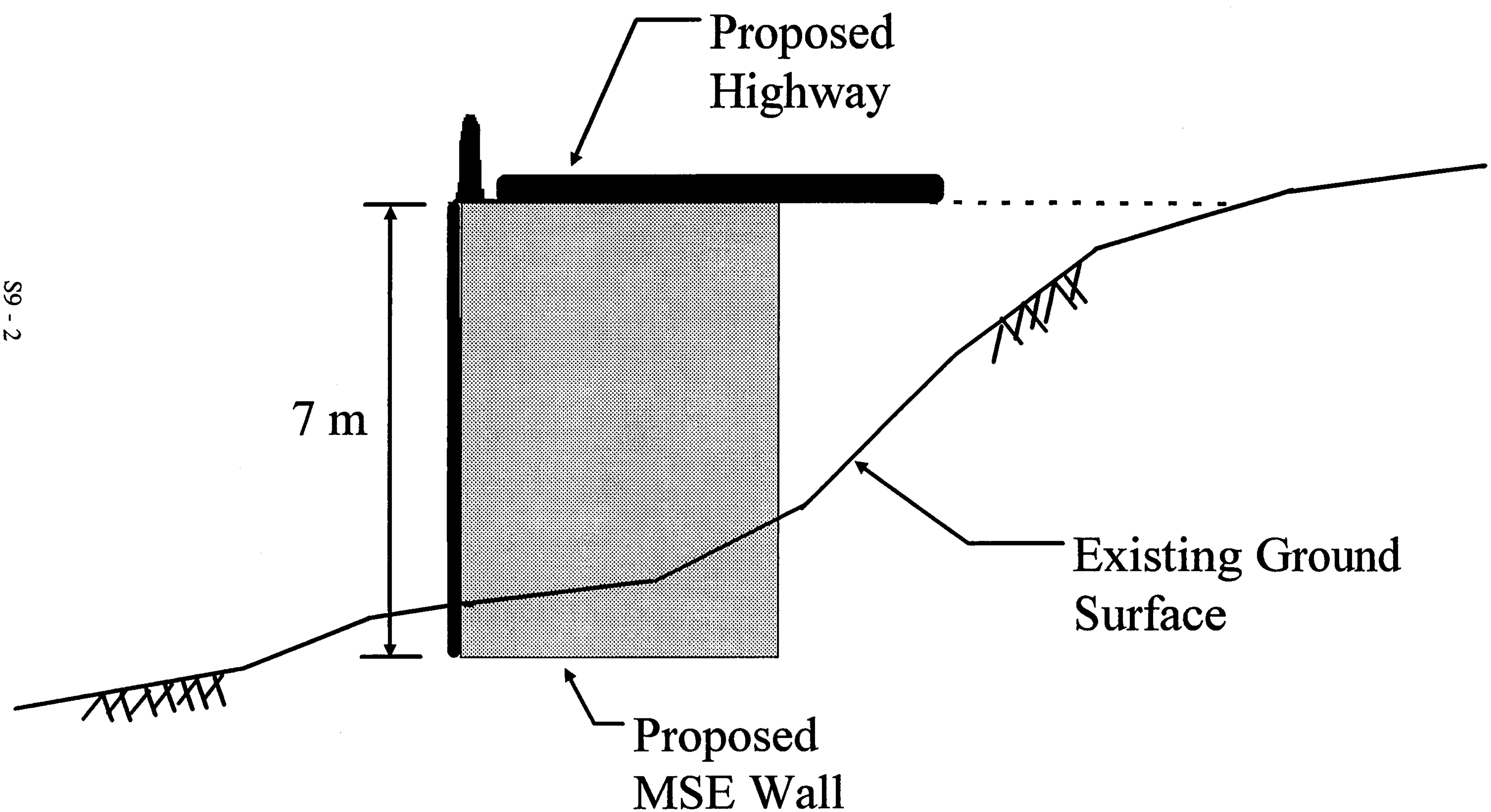
(c) The factor of safety for sliding

Manual Reference:

Section 6.6.1

Figure 6-13

Student Exercise 9 Figure S9-1



SOLUTION TO STUDENT EXERCISE 9

a. For preliminary sizing consider $L = 0.7\ H$

$L = 0.7\ (7\ m) = 4.9\ m$ ***(Section 6.6.1)***

Since reinforcements are manufactured in 0.5 m increments, use $L = 5\ m$

b. Compute coefficient of earth pressure for retained fill

$K_{af} = \tan^2 (45° - \phi/2) = \tan^2 (45° - 30°/2) = 1/3$

Compute horizontal earth pressure loads (see Figure S9-2)

(Figure 6-13)

i. Earth pressure (soil), $F_1 = \gamma\ H^2\ K_a / 2$

$= (20\ kN/m^3)(7\ m)^2 / 6$

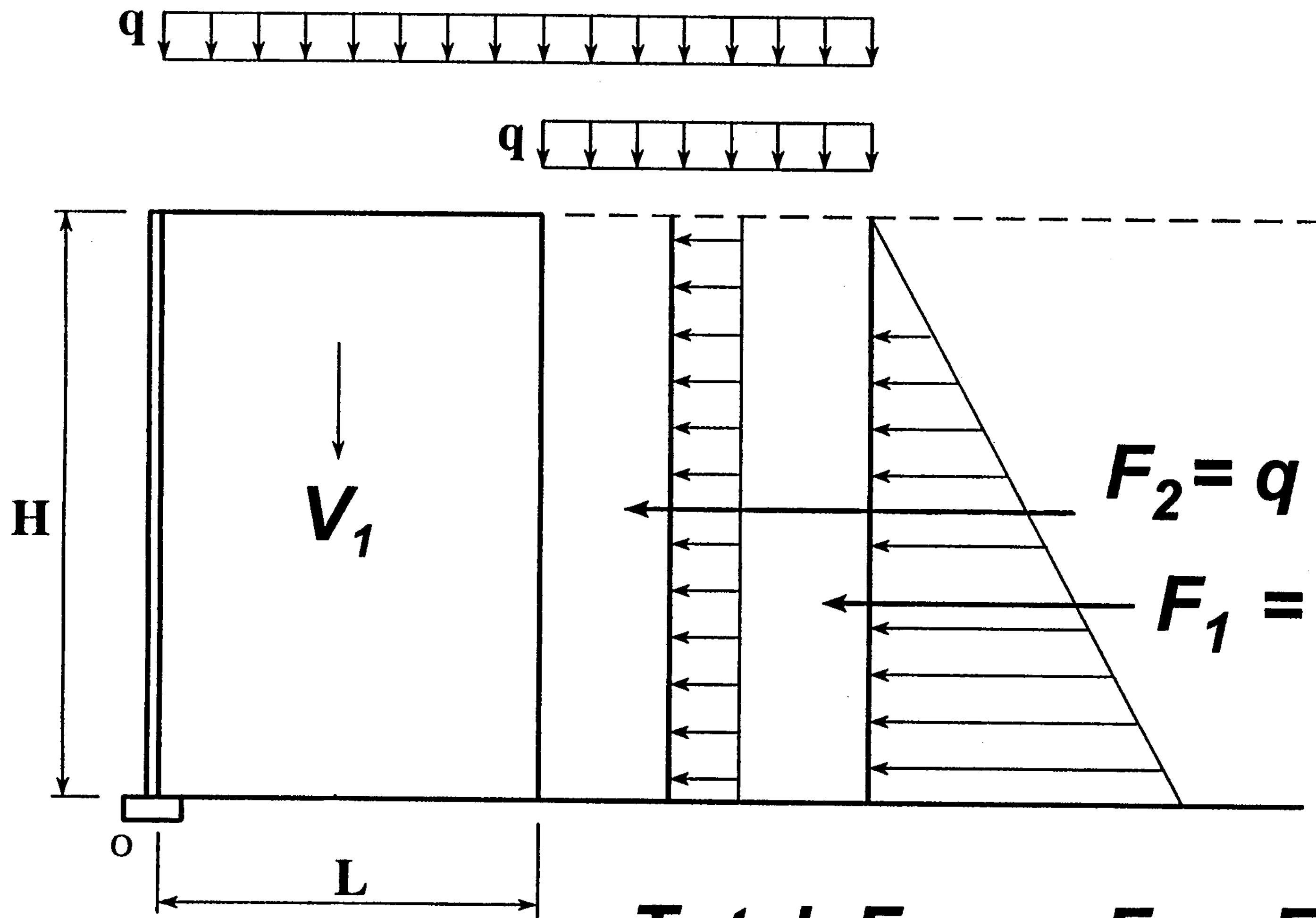
$= 163.3\ kN/m$

ii. Earth pressure (traffic) $F_2 = q\ H\ K_a$

$= (10\ kN/m^2)(7\ m)/3$

$= 23.3\ kN/m$

Student Exercise 9 — Figure S9-2



$$F_2 = q\,H\,K_{af}$$

$$F_1 = \gamma\,H^2\,K_{af} / 2$$

Total Force, $F_T = F_1 + F_2$

The total horizontal force on reinforced fill, F_T, is given by

$$F_T = F_1 + F_2 = 163.3 \text{ kN/m} + 23.3 \text{ kN/m} = 186.6 \text{ kN/m}$$

c. The FS for sliding is the ratio of the sum of the horizontal resisting forces to sliding forces, see Figure S9-3.

(Figure 6-13)

Resisting force

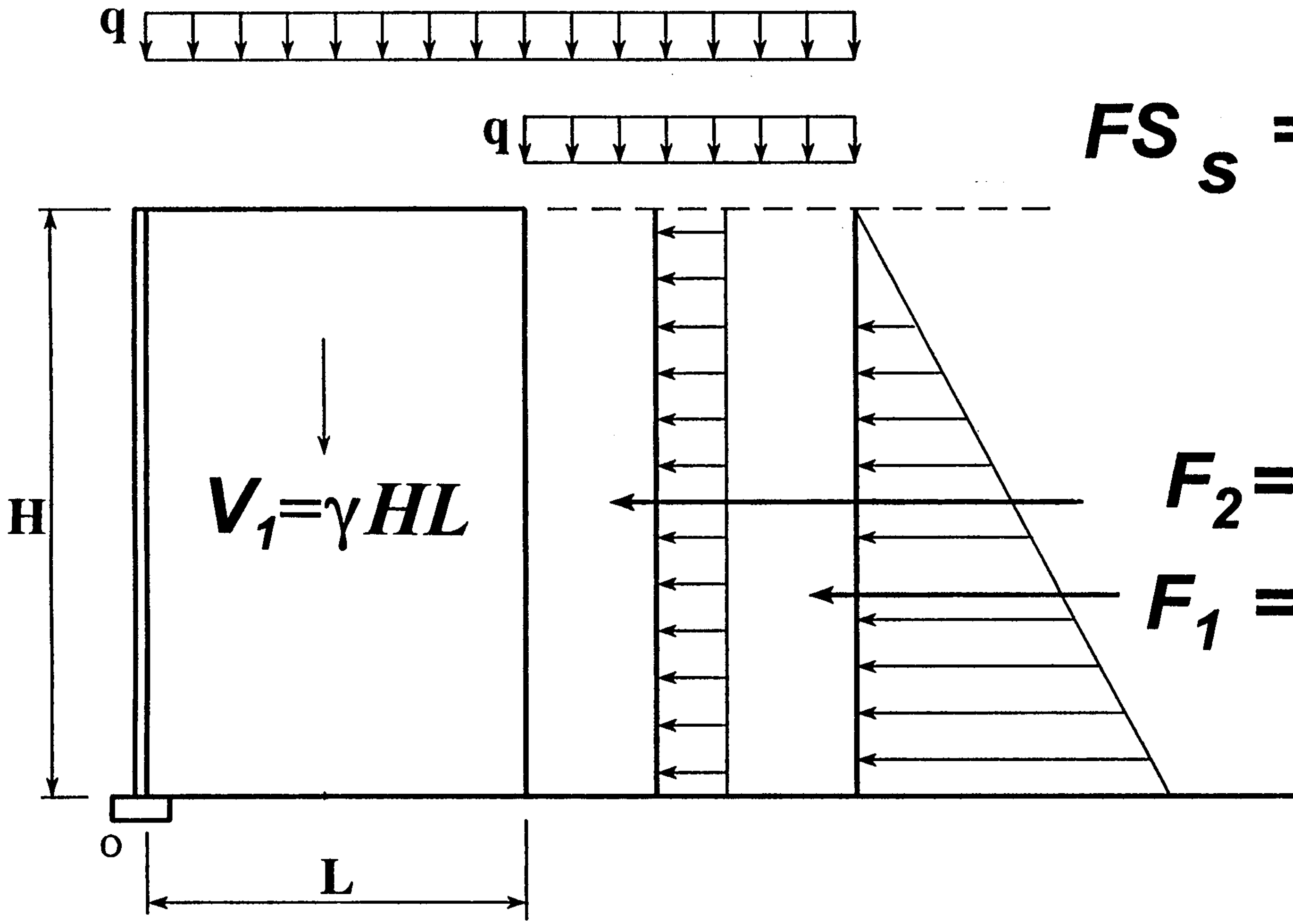
$$\begin{aligned} V_1 \tan\phi &= \gamma\, H\, L \tan\phi \\ &= (20 \text{ kN/m}^3)(7 \text{ m})\,(5 \text{ m}) \tan 30^\circ \\ &= 404.14 \text{ kN/m} \end{aligned}$$

Driving force

$$F_T = F_1 + F_2 = 163.3 \text{ kN/m} + 23.3 \text{ kN/m} = 186.6 \text{ kN/m}$$

$$FS_S = \frac{V_1 \tan\phi}{F_1 + F_2} = \frac{404.14 \text{ kN/m}}{186.6 \text{ kN/m}} = 2.17$$

Student Exercise 9 — Figure S9-3



$$FS_s = \frac{V_1 \tan\phi}{F_1 + F_2}$$

$$F_2 = q\,H\,K_{af}$$

$$F_1 = \gamma\,H^2\,K_{af} / 2$$

STUDENT EXERCISE 10

From the previous exercise it was determined that the 7 m high wall is externally stable with 5 m long reinforcements.

Consider that linear ribbed reinforcements will be used and that the frictional strength of the select fill was determined to be at least 34 degrees and the maximum factor F*=1.5

Compute at a depth of 3.5 m the following:

(a) The effective length of reinforcements, for internal stability computations.

(b) The coefficient K for internal stability computations.

(c) The coefficient F* for internal stability computations.

Manual Reference:

Figure 6-22a, Figure 6-23, Section 6.4.3

SOLUTION TO STUDENT EXERCISE 10

a. Effective length L_e at a depth of 3.5 m

Depth ratio = Z_i / H = 3.5 m/ 7 m = 0.5 H

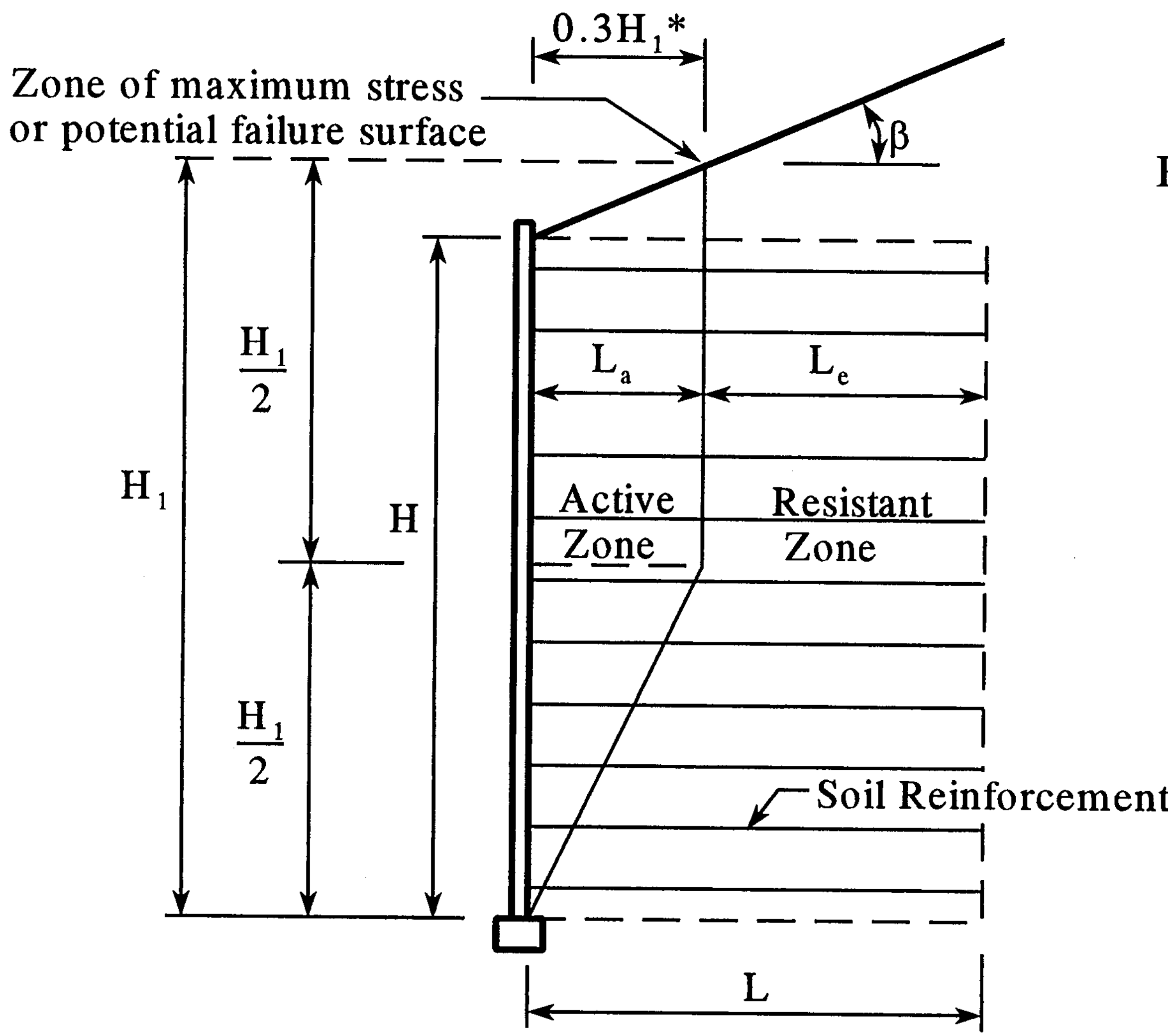
From Figure S10-1 ***(Figure 6-22a)***

at H/2, the active zone width, L_a = 0.3 H
= 0.3(7m)
= 2.1 m

therefore: L_e = L - L_a = 5.0 m - 2.1 m = 2.9 m

Student Exercise 10

Figure S10-1



(a)

$$H_1 = H + \frac{\tan\beta \times 0.3H}{1 - 0.3\tan\beta}$$

* If wall face is battered, an offset of $0.3H_1$ is still required, and the upper portion of the zone of maximum stress should be parallel to the wall face

b. Compute K coefficient at $Z_i = 3.5$ m

From Figure S10-2 ***(Figure 6-23)***

$K_a = \tan^2 (45° - \phi/2) = \tan^2 (45° - 34°/2) = 0.28$

$K = 1.7\, K_a = 0.48$ at the top of structure and

$K = 1.2\, K_a = 0.34$ at a depth of 6 m

therefore by interpolation:

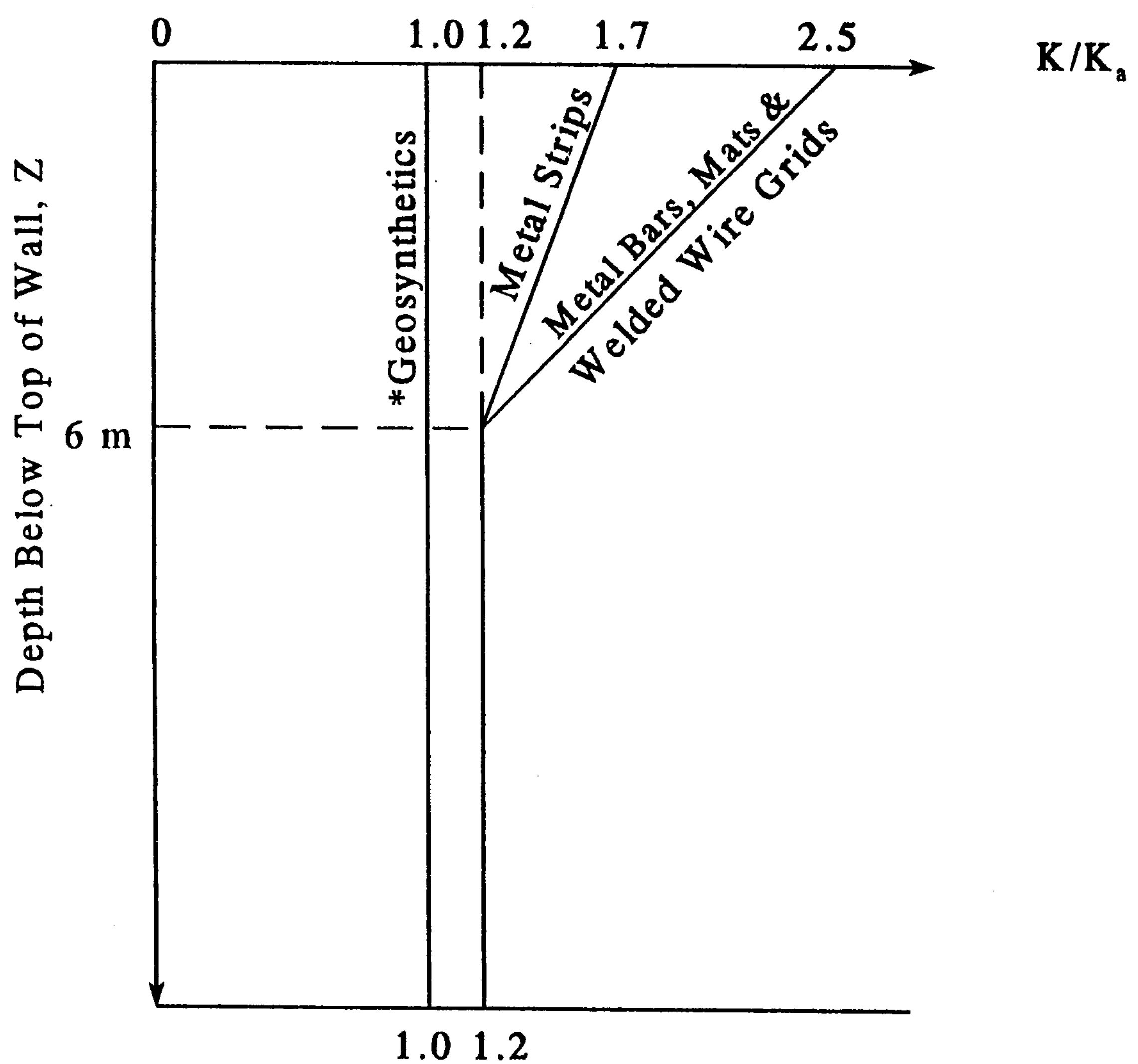
$$\frac{(1.7\, K_a - 1.2\, K_a)}{6.0} = \frac{x_{zi}}{6.0 - Z_i}$$

$$\frac{(0.48 - 0.34)}{6.0} = \frac{x_{zi}}{6.0 - 3.5}$$

$\Rightarrow \quad x_{zi} = 0.058$

$K_{zi} = K_a + x_{zi} = 0.34 + 0.058 = 0.40$

Student Exercise 10 Figure S10-2



c. $F^* = 1.5$ at the top of structure ***(Section 6.4.3)***

$F^* = \tan \phi = \tan 34° = 0.67$ at 6 m depth

therefore by interpolation:

$$\frac{(1.5 - 0.67)}{6.0} = \frac{x_{zi}}{6.0 - 3.5}$$

$$\Rightarrow \qquad x_{zi} = 0.35$$

$F^* = F^* \text{ @ } 6.0 \text{ m} + x_{zi} = 0.67 + 0.35 = 1.02$

STUDENT EXERCISE 11

Given: 4 mm thick, 50 mm wide galvanized steel strip, Galvanization thickness = 86 μm
Steel for strip is Grade 60 with F_y = 450 MPa
Design life = 75 years
Mildly corrosive backfill

Compute:

a. The allowable tensile force per unit width at the end of its anticipated 75 year design life.

b. The magnitude of force that each reinforcement can sustain?

Manual Reference:

Sections 6.5.1, 6.7, Equation 6-7

SOLUTION TO STUDENT EXERCISE 11

a. For mildly corrosive backfill the corrosion losses are: ***(Section 6.5.1)***

Zinc loss : 15 μm/year (first 2 years)

4 μm/year (thereafter)

Steel loss : 12 μm/year

Calculate service life for 86 μm zinc coating:

$$\text{Life} = \frac{86\,\mu\text{m} - 2\text{ years}\left(15\,\dfrac{\mu\text{m}}{\text{year}}\right)}{4\,\dfrac{\mu\text{m}}{\text{year}}}$$

Life = 16 years

Therefore, total required life of carbon steel is:

Required life = 75 years - 16 years = 59 years

The section loss of steel is:

$$t_S = 2\ (12\ \mu\text{m/year})\ (56\ \text{years}) = 1.42\ \text{mm}$$

Thus, section remaining after 75 years is

$$t_C = 4.00\ \text{mm} - 1.42\ \text{mm} = 2.58\ \text{mm}$$

The allowable tensile forces per unit width is:

(Equation 6-7)

$$T_a = FS\ \frac{A_c F_y}{b} = \frac{0.55\ b\ t_c F_y}{b} = 0.55\ t_c F_y$$

For 60 grade steel: $F_y = 450$ MPa

Therefore:

$$T_a = (0.55)\ (0.00258\ \text{m})\ (450{,}000{,}000\ \text{N/m}^2)$$
$$= 639{,}000\ \text{N/m} = 639\ \text{kN/m}$$

b. Each reinforcement can sustain a force F of:

$$F = b.T_a = 0.05 \text{ m } (639 \text{ kN/m}) = 32 \text{ kN}$$

STUDENT EXERCISE 12

From Station 6+700 to 7+00 the highway merges with the approaches to a major bridge. To accommodate increased traffic demands the approaches and the bridge have to be widened from two lanes to four lanes. The original approaches to the bridge were on embankments with 2H:1V side slopes (Figure S12-1).

An anchored soldier-pile concrete lagging wall was selected. Figure S12-2 shows a cross-section of the wall.

Compute:

(a) The depth of embedment of the soldier pile, X

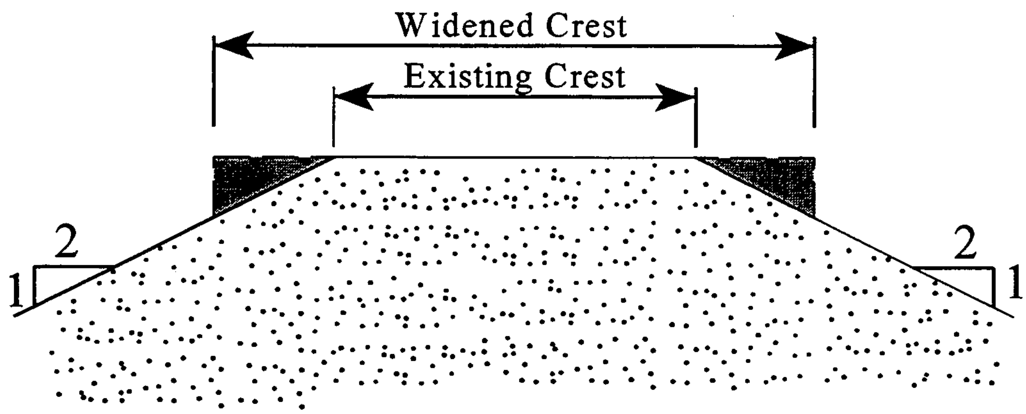
(b) The anchor force, T

(c) Point of zero shear and the maximum moment

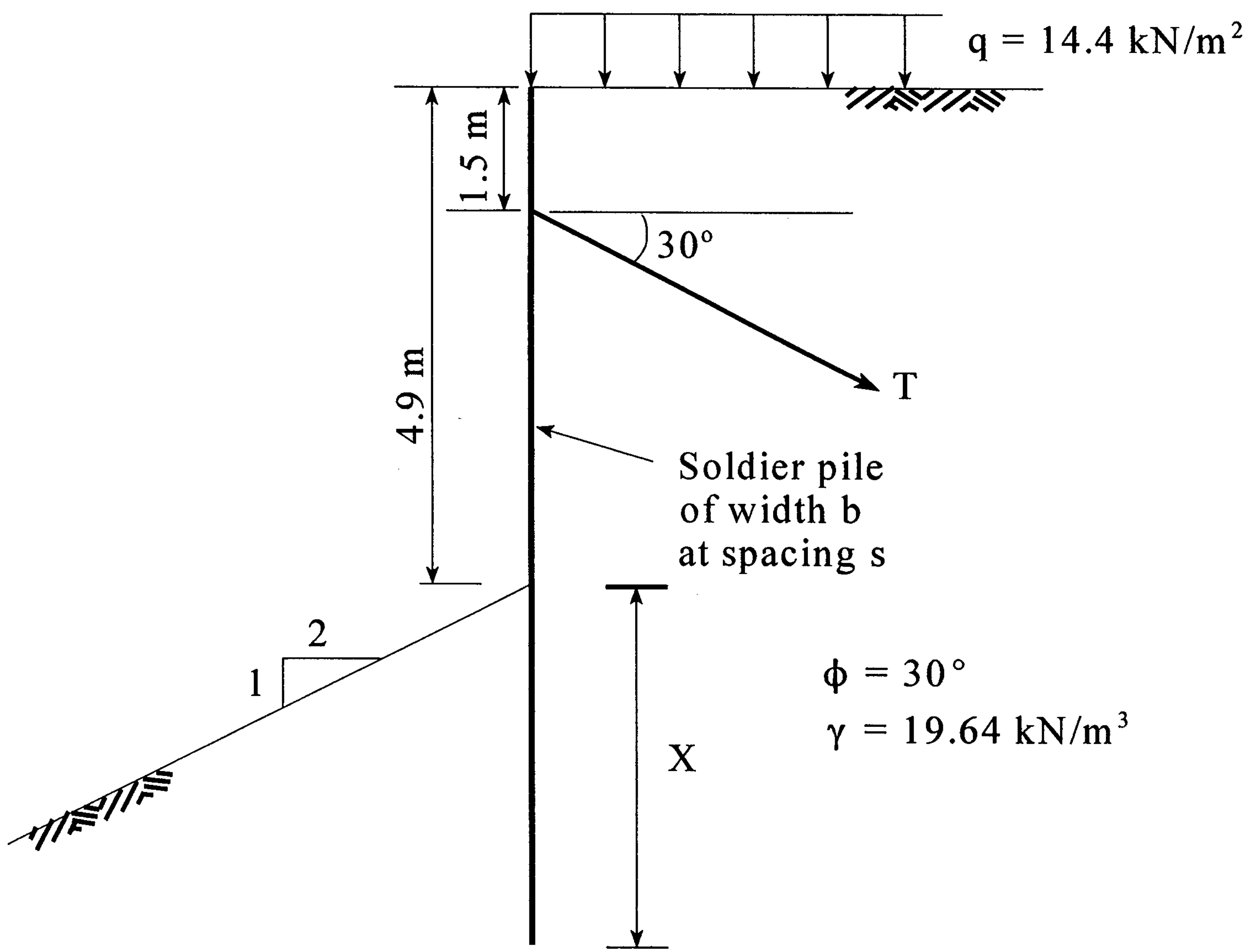
Manual Reference:

Chapter 2, Equation 2-5, Figure 2-6
Sections 7.6.1 and 7.6.2;
Page 7-45 **("Soldier Pile Spacing")**
Figures 7-21 and 7-29
Example Problem 7-3

Student Exercise 12
Figure S12-1



Student Exercise 12   Figure S12-2



Solution to Student Exercise 12

Compute K_a and K_p :

$K_a = \tan^2 (45° - \phi/2) = \tan^2 (45° - 30°/2)$ ***(Eq. 2-5)***

$= 1/3$

Use Figure S12-3 to determine K_p ***(Figure 2-6)***

β = Angle of front slope with horizontal
$= \tan^{-1}(-1/2)$
$= -26.57°$

$\beta/\phi = -26.57°/30°$
$= -0.89$

$\delta/\phi = 0 /30°$ (Assume $\delta = 0$)
$= 0$

For $\phi = 30°$ and $\beta/\phi = 0.89$, $K_p \approx 1.5$ for $\delta/\phi = -1$

Reduction factor for $\delta/\phi = 0$ and $\phi = 30°$, $R = 0.467$

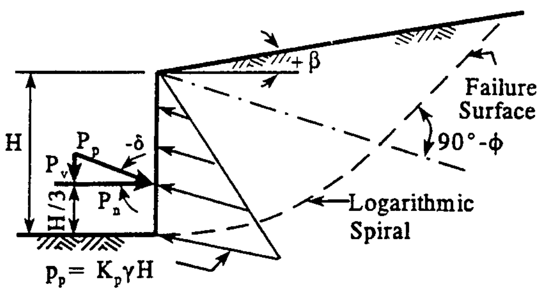
Thus, $K_p = R$ (K_p for $\delta/\phi = -1$)
$= (0.467)\,(1.5)$
$= 0.70$

Student Exercise 12

Figure S12-3

REDUCTION FACTOR (R) OF K_p
FOR VARIOUS RATIOS OF $-\delta/\phi$

ϕ \ δ/ϕ	-0.7	-0.6	-0.5	-0.4	-0.3	-0.2	-0.1	0.0
10	.978	.962	.946	.929	.912	.898	.881	.864
15	.961	.934	.907	.881	.854	.830	.803	.775
20	.939	.901	.862	.824	.787	.752	.716	.678
25	.912	.860	.808	.759	.711	.666	.620	.574
30	.878	.811	.746	.686	.627	.574	.520	.467
35	.836	.752	.674	.603	.536	.475	.417	.362
40	.783	.682	.592	.512	.439	.375	.316	.262
45	.718	.600	.500	.414	.339	.276	.221	.174

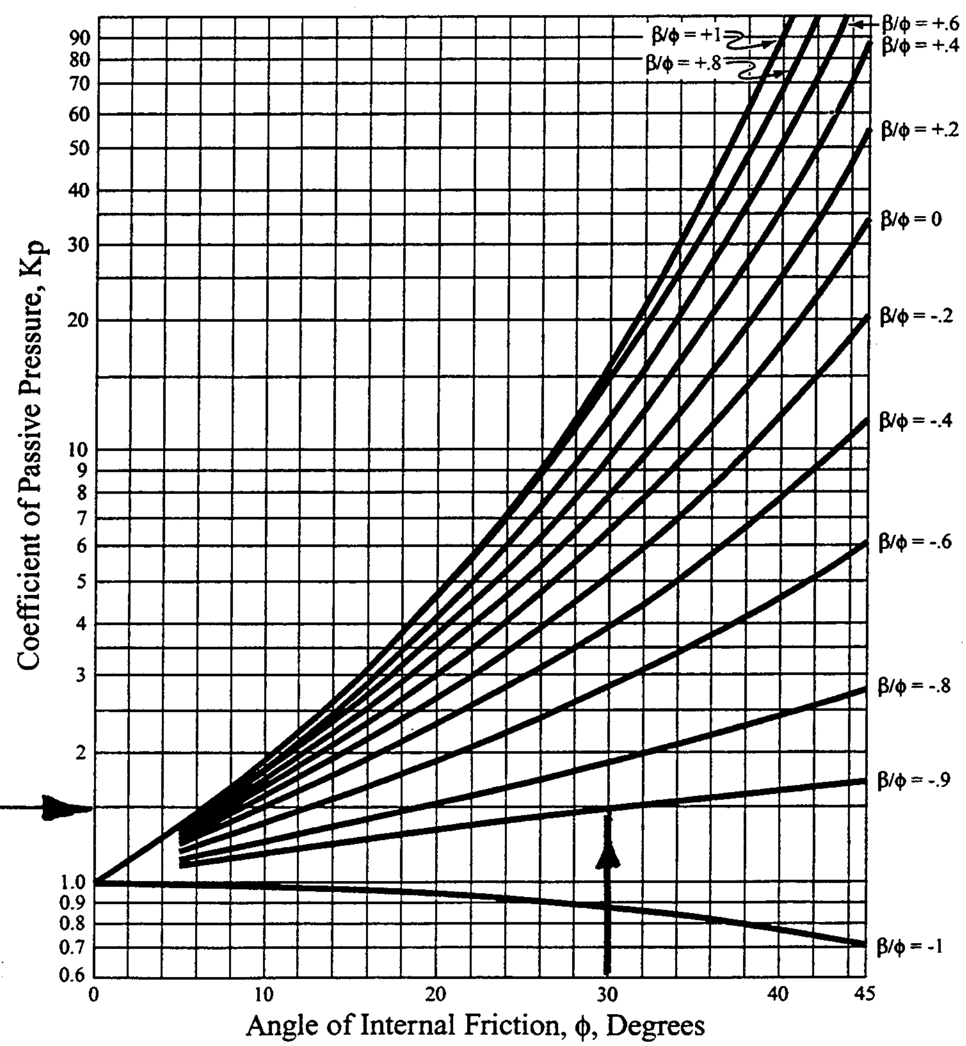


$P_p = K_p \gamma H^2/2$; $P_n = P_p \cos\delta$; $P_v = P_p \sin\delta$

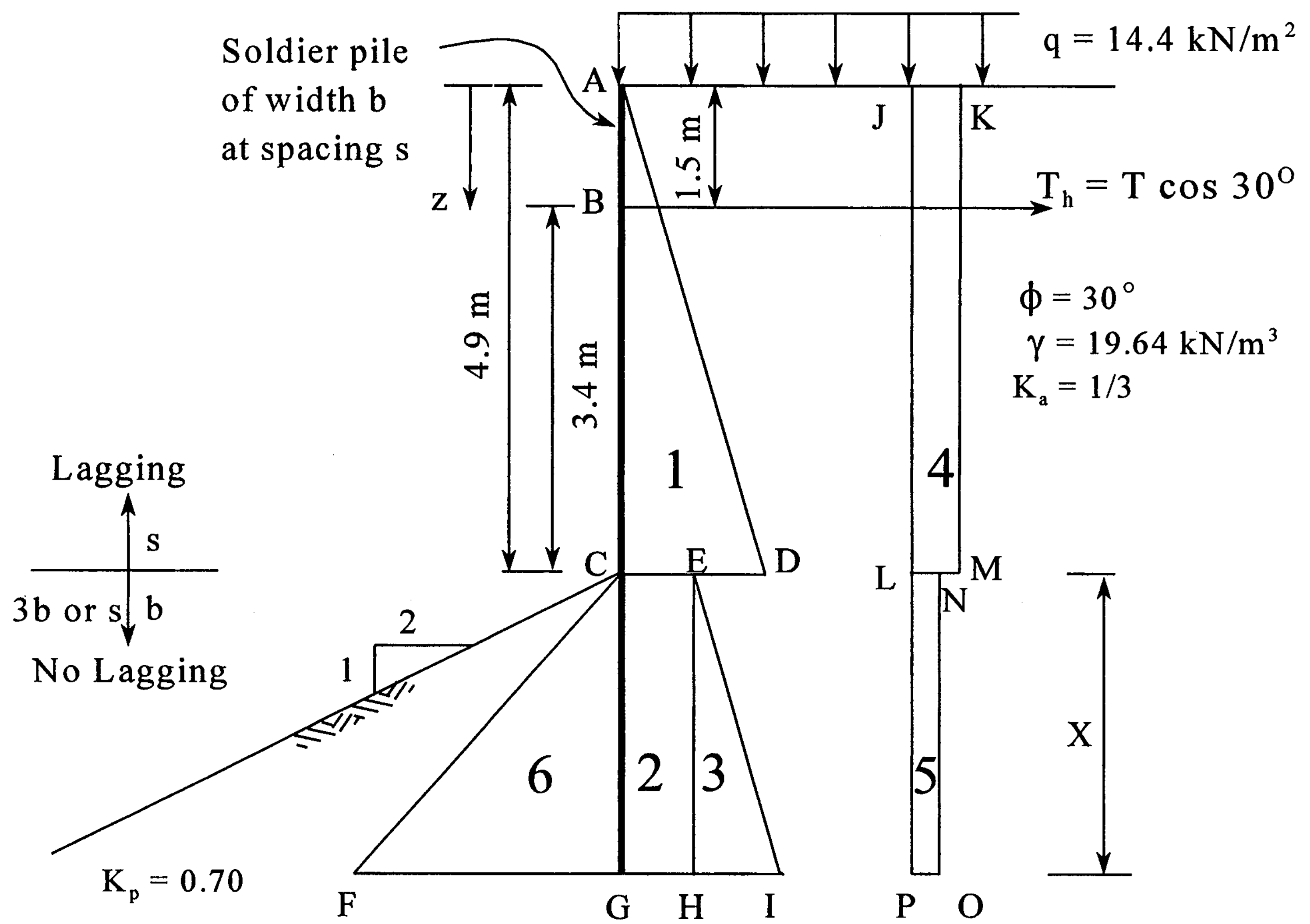
Example: $\phi = 25°$; $\beta/\phi = -0.2$; $\delta/\phi = -0.3$

$K_p = R(K_p \text{ for } \delta/\phi = -1) = (0.711)(3.62) = 2.58$

Note: Curves shown are for $\delta/\phi = -1$



Student Exercise 12 — Figure S12-3



Location		Force [(kN/m^3).m.m = kPa.m]		
CD	Ac - Lag	$K_a \gamma H s$ =	(1/3)19.64 (4.9) s =	32.08 s
CE=GH	Ac-No Lag			
HI	Ac-No Lag			
JK	Ac - Lag			
NL=OP	Ac-No Lag			
FG	Passive			

s = center to center spacing of soldier piles

b = width of soldier pile

Assume 3b < s; other wise use s instead of 3b on Passive side

Location		Force [(kN/m^3).m.m = kPa.m]		
CD	Ac - Lag	$K_a \gamma H s$ =	(1/3)19.64 (4.9) s =	32.08 s
CE=GH	Ac-No Lag	b(CD/s) =	b(32.08 s / s) =	32.08 b
HI	Ac-No Lag	$K_a \gamma X b$ =	(1/3) 19.64 X b =	6.55 X b
JK	Ac - Lag	$K_a q s$ =	(1/3) 14.4 s =	4.80 s
NL=OP	Ac-No Lag	b (JK/s) =	b (4.80 s / s) =	4.80 b
FG	Passive	$(K_p/FS) \gamma X (3b)$ =	(0.70/1.5) 19.64 X (3) b =	27.52 X b

s = center to center spacing of soldier piles
b = width of soldier pile
Assume 3b < s; otherwise use s instead of 3b on Passive side

Force, kN					Sign	Lever Arm @ B, m		
P_1	=	½(32.08 s) 4.9	=	78.60 s	+	L_1	=	⅔(4.9) - 1.5 = 1.77
P_2	=	(32.08 b) X	=	32.08 b X	+	L_2	=	½ X + 3.4
P_3	=	½ (6.55 X b) X	=	3.28 b X^2	+	L_3	=	⅔ X + 3.4
P_4	=	(4.80 s) 4.9	=	23.52 s	+	L_4	=	½(4.9) - 1.5 = 0.95
P_5	=	(4.80 b) X	=	4.80 b X	+	L_5	=	½ X + 3.4
P_6	=	½ (27.52 b X) X	=	13.76 b X^2	-	L_6	=	⅔ X + 3.4
T_h	=	T cos 30°	=	???	-	L_T	=	0

Force Equation (to find T)

$\Sigma P = 0$

$P_1 + P_2 + P_3 + P_4 + P_5 - P_6 - T_h = 0$

$T_h = P_1 + P_2 + P_3 + P_4 + P_5 - P_6$

Substituting force values:

$$\boxed{\begin{array}{l} T_h = 102.12\, s + 36.88\, b\, X - 10.48\, b\, X^2 \\ \\ T = T_h / \cos 30^\circ \end{array}} \quad \text{(Eq. 1)}$$

Moment Equation (to find X)

$\Sigma M @ B = 0$

$P_1 L_1 + P_2 L_2 + P_3 L_3 + P_4 L_4 + P_5 L_5 - P_6 L_6 = 0$

Substituting values:

$$\boxed{\begin{array}{l} \Sigma M_B = 0 = \\ -6.98\, b\, X^3 - 17.19\, b\, X^2 + 125.39\, b\, X + 161.46\, s \end{array}}$$

(Eq. 2)

Procedure to find X and T

Step 1: Select Pile Width, b, and c/c Spacing, s

Check if $3b < s$

Solve Eq. 2 (Moment equation) for X

Step 2: Using b, s and X from Step 1

Solve Eq. 1 (Force equation) to find T_h and T

Select : $b = 0.457$ m (1.5 foot soldier pile)

$s = 2.438$ m (8 feet spacing)

Check: $3\,b = 3(0.457\text{ m}) = 1.37\text{ m} < 2.438$ O.K.

Solving Eq. 2 (Moment equation) by trial and error:

$$\boxed{X = 5.3 \text{ m}}$$

Substitute b, s and X in Eq. 1 (Force equation) and solve:

$$T_h = 203.8 \text{ kN}$$

$$T = T_h / \cos 30^o$$

$$T = 235.3 \text{ kN}$$

Point of zero shear

Assume zero shear occurs at a distance z from point A and within AC

Take sum of forces within distance z:

$$S_z = \frac{1}{2}\left(\frac{19.64}{3}\right) s z^2 + \left(\frac{14.4}{3}\right) s z - 203.8 = 0$$

For s = 2.438 m

$$S_z = 7.97 z^2 + 11.7 z - 203.8 = 0$$

Solving the quadratic equation:

$z = 4.38$ m (within AC .... O.K.)

Maximum Moment (M_{max})

M_{max} occurs at point of zero shear

Compute moment at a depth of z = 4.38 m

$$M_{max} = \frac{1}{2}\left(\frac{19.64}{3}\right) s z^2 \left(\frac{z}{3}\right) + \left(\frac{14.4}{3}\right) s z \left(\frac{z}{2}\right) - 203.8 (z - 1.5)$$

Substituting values of s and z:

$$\boxed{M_{max} = -251.17 \text{ kN.m}}$$

Other Considerations

1. Check embedment for vertical capacity

   Vertical load is imposed by the vertical component of anchor force, weight of the soldier pile and the lagging.

   Refer to Module 8 (Deep Foundations).

2. Embedment may be governed by global stability.

   Use slope stability analysis to evaluate global stability.

   Refer to Module 3 (Soil Slopes and Embankments).

3. The free length of the anchor may be governed by global stability.

   The bonded zone must be located behind the critical failure surface.

   Refer to Example Problem 7-3 in Reference Manual for design of soil anchors.

STUDENT EXERCISE 13

Consider Student Exercise 12. Use Coulomb's theory to obtain passive resistance.

Compute:

(a) The depth of embedment of the soldier pile, X

(b) The anchor force, T

(c) The maximum moment, M_{max}

(d) Compare the above quantities with Student Exercise 12.

Manual Reference:

Chapter 2, Equation 2-5, Figure 2-2
Sections 7.6.1 and 7.6.2;
Figures 7-21 and 7-29
Example Problem 7-3

SOLUTION TO STUDENT EXERCISE 13

From Figure 2-2, using Passive Case with $\delta = 0$

$$K_p = \left[\frac{\cos\phi}{1 - \sqrt{\sin\phi(\sin\phi + \cos\phi \tan\beta)}} \right]^2$$

β = Angle of front slope with horizontal = $\tan^{-1}(-1/2)$
= $-26.57°$

Substituting values, we obtain:

$$K_p = \left[\frac{\cos 30°}{1 - \sqrt{\sin 30° [\sin 30° + \cos 30° \tan(-26.57°)]}} \right]^2$$

$K_p = 1.12$

Use the above value of K_p and repeat solution for Student Exercise 12. Comparison of results for $K_p = 1.12$ and 0.70 is presented in Table S13-1.

TABLE S13 - 1

Quantity	K_p = 1.12	K_p = 0.7
X	3.8 m	5.3 m
T	218.8 kN	235.3 kN
M_{max}	-211.35 kN.m	-251.17 kN.m

Key Point

Use of Coulomb's theory for computing passive resistance is not conservative.

STUDENT EXERCISE 14

Refer to Figure S14-1. (Same as Figure S3-1 in Student Exercise 3)

(a) Develop an apparent earth pressure envelope assuming that the wall has multiple supports.

(b) Develop recommendations for design pressures.

Manual Reference:

Chapter 2

Sections 2.4 and 2.5; Eq. 2-5;

Figures 2-3, 2-7 and 2-8.

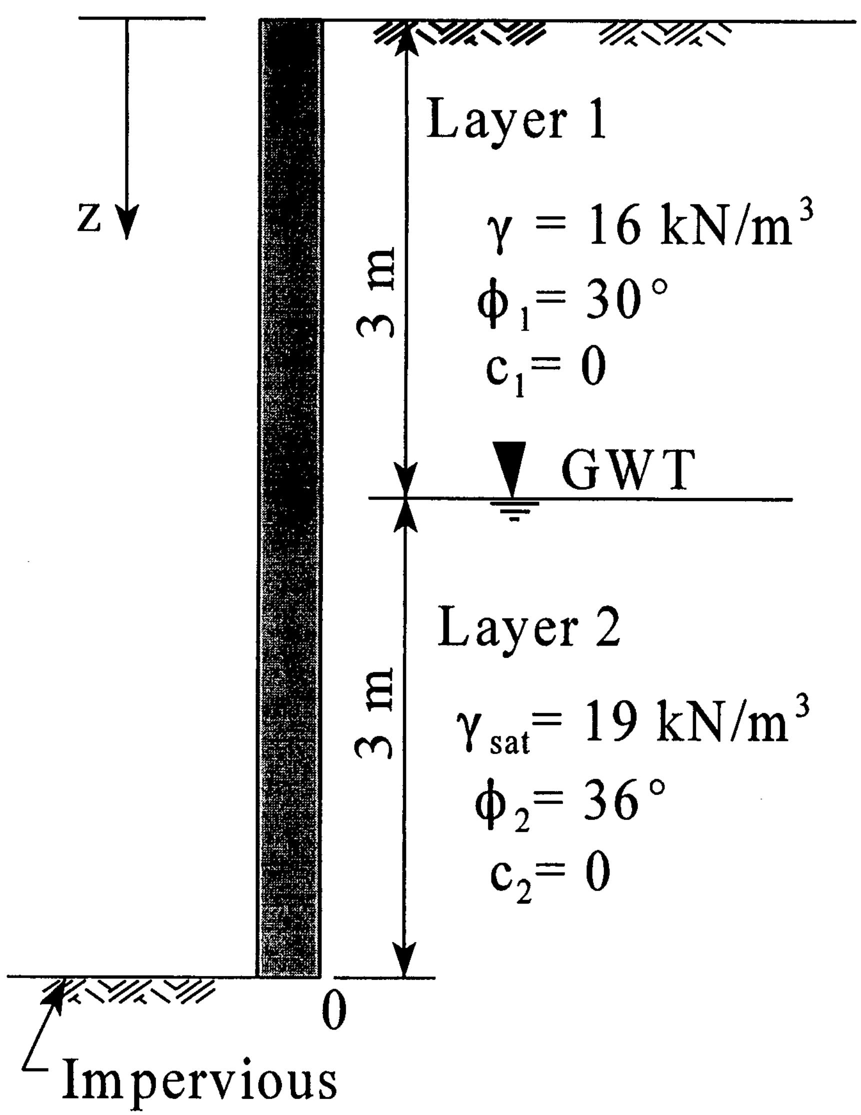
Footnote on Page 2-1

Chapter 7

Figure 7-28

Section 7.6.2 (see "Layered Soils" on Page 7-44)

Student Exercise 14 Figure S14-1



Solution to Student Exercise 14

From Section 7.6.2
(Layered Soils on Page 7-44)

Step 1. Compute the Rankine active earth force, P_a

Step 2. Select most appropriate case from ***Figure 7-28***

Step 3. Compute equivalent total force in apparent pressure envelope, P_t

Step 4. Distribute force P_t as per the distribution corresponding to the case selected in Step 2.

Step 1: Compute the Rankine active earth force, P_a

The lateral pressure distribution is same as in Student Exercise 3 and is shown in Figure S14-2.

The Rankine active earth force, P_a, is obtained by summing areas 1, 2 and 3.

$$P_a = P_1 + P_2 + P_3$$

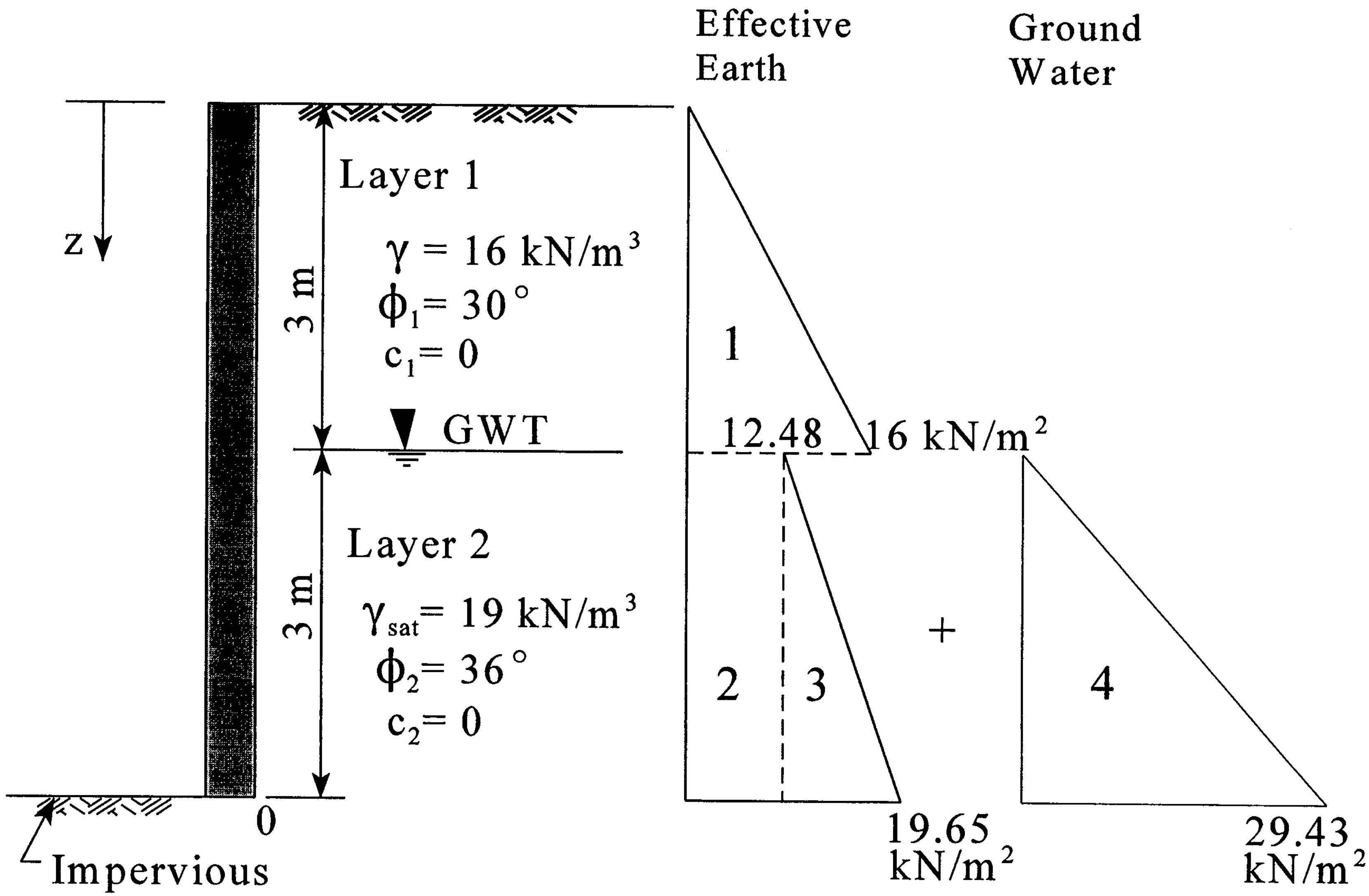
$$= \text{Area 1} + \text{Area 2} + \text{Area 3}$$

$$= \tfrac{1}{2}(3\text{ m})(16\text{ kN/m}^2) + (12.48\text{ kN/m}^2)(3\text{ m}) + \tfrac{1}{2}(19.65\text{ kN/m}^2 - 12.48\text{ kN/m}^2)(3\text{ m})$$

$$= 24\text{ kN/m} + 37.44\text{ kN/m} + 10.76\text{ kN/m}$$

$$= \mathbf{72.20\text{ kN/m}}$$

Student Exercise 14 — Figure S14-2



(a) (b) (c)

Step 2. Select most appropriate case from *Figure 7-28* (reproduced in Figure S14-3).

Check the box which represents the most appropriate case for this exercise

☐	SAND	***(Fig 7-28a)***
☐	SOFT TO MEDIUM CLAY	***(Fig 7-28b)***
☐	STIFF CLAY	***(Fig 7-28c)***

Step 3. Compute equivalent total force in apparent pressure envelope, P_t

For the most appropriate case, select the P_t/P_a ratio from Figure S14-3

P_t/P_a = _____

P_t = (____) (P_a)

P_t = _____ kN/m

STUDENT EXERCISE14

FIGURE S14-3 (OR FIGURE 7-28 OF MANUAL)

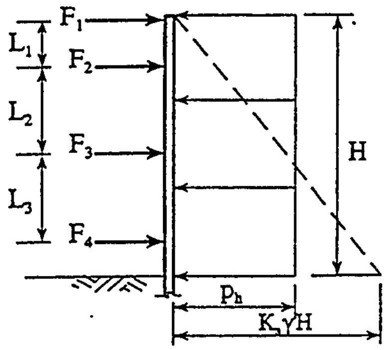
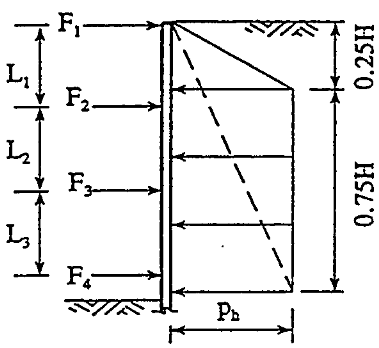
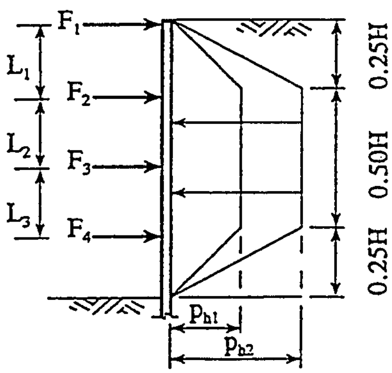
EMPRICAL PRESSURE DISTRIBUTION		TOTAL FORCE
	(a) SAND $p_h = 0.65 K_A \gamma H$ where $K_A = \tan^2\left(45 - \frac{\phi}{2}\right)$	$P_t = 0.65 K_A \gamma H^2$ $P_a = 0.50 K_A \gamma H^2$ $\frac{P_t}{P_a} = 1.30$ where: P_t = total horizontal force from trapezoidal pressure distribution. P_a = total horizontal force from Rankine (triangular) distribution. P_t/P_a is a ratio representing the increase in total horizontal force for excavation support systems with multiple levels of bracing.
	b) SOFT TO MEDIUM CLAY ($N_0 > 6$) For clays, base the selection on $N_0 = \gamma H/c \quad p_h = K_A \gamma H$ $K_A = 1 - m\frac{4c}{\gamma H} = 1 - \frac{4m}{N_o}$ m = 1 except where cut is underlain by soft normally consolidated clay, then m = 0.4	For m = 1.0: $P_t = 0.875 \gamma H^2 \left(1 - \frac{4}{N_0}\right)$ $P_a = 0.50 \gamma H^2 \left(1 - \frac{4}{N_0}\right)$ $\frac{P_t}{P_a} = 1.75$
	(c) STIFF CLAY ($N_0 < 4$) For $4 < N_0 < 6$, use larger of diagrams (b) and (c). $p_{h_1} = 0.2 \gamma H; \; p_{h_2} = 0.4 \gamma H$ Use lower value when movements are minimal and construction period is short	$P_t = 0.15 \gamma H^2$ to $0.30 \gamma H^2$ For $N_0 \leq 4: P_a = 0$

Figure 7-28: Pressure Distribution for Braced Walls. (Modified After Terzaghi and Peck, 1967)

Step 4. Distribute force P_t as per the distribution to the case selected in Step 2. For sands the pressure is distributed in a rectangular fashion.

Width of the rectangular diagram, p_h is computed as follows:

$$p_h = \frac{P_t}{\text{Wall Height}}$$

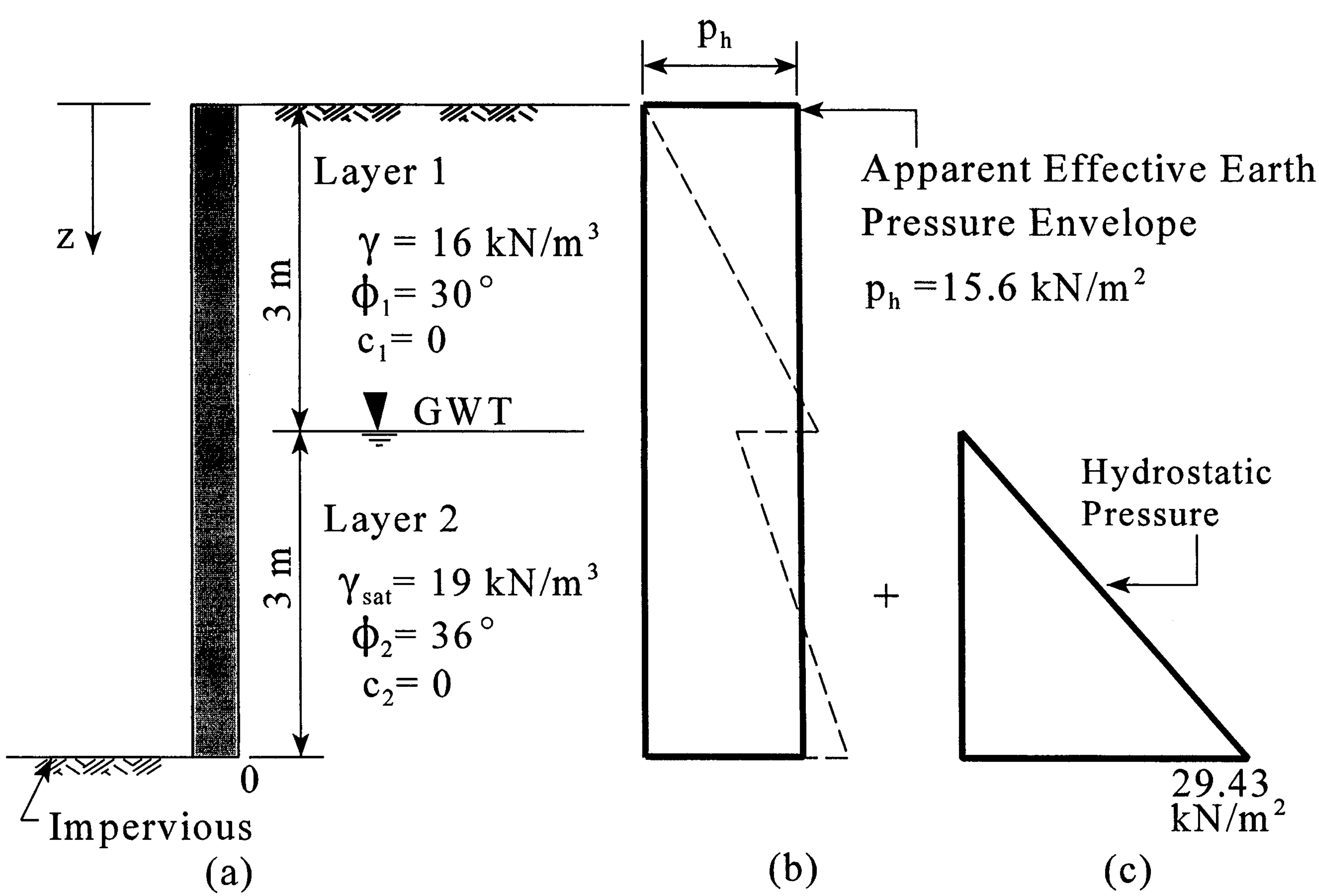
$$p_h = \frac{(\qquad\qquad)}{(\qquad)}$$

$$p_h = \_\_\_\_\_\_\_\_ \quad kN/m^2$$

Thus the apparent pressure envelope is rectangular over the entire height of the wall and and a pressure of ______ kN/m^2.

(b) For this problem, since water pressure also exists, the wall should be designed to resist both the earth and water pressures. Figure S14-5 shows the layout of the pressure diagrams.

Student Exercise 14 Figure S14-5



Key Points

- For walls with multiple levels of support and layered soils compute the total lateral force and distribute it using the most appropriate apparent pressure envelope.

STUDENT EXERCISE 15

To maintain the grade of the proposed highway, a cut in the existing hillside between Stations 6+600 and 6+900 was necessary. The profile of the cut is shown in Figure S15-1. A soil nail wall was selected to support the cut slope.

Perform a preliminary soil nail wall design using the simplified design chart procedure.

Manual Reference:

Sections 8.2.2, 8.2.3 and 8.2.4

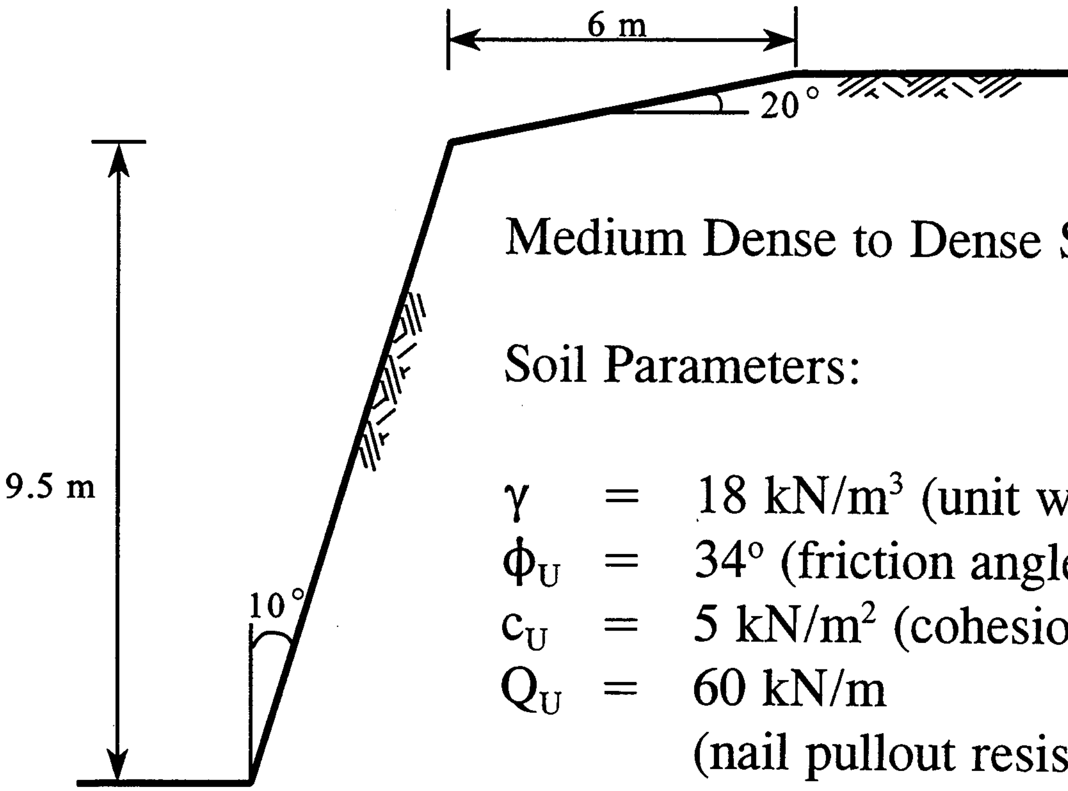
Equations 8-7, 8-8, 8-9, and 8-10

Figures 8-16(a), 8-16(c), 8-28(a) and 8-28(b)

Table 8-5

Student Exercise15

Figure S15-1



Medium Dense to Dense Silty Sand

Soil Parameters:

γ	=	18 kN/m³ (unit weight)
ϕ_U	=	34° (friction angle)
c_U	=	5 kN/m² (cohesion)
Q_U	=	60 kN/m (nail pullout resistance based on field pullout testing)

Assumptions:

- Permanent, Non-Critical Structure
- Ground water table below bottom of cut
- AASHTO Group I loading condition governs
- Soil nail inclination angle = 15° (typical)
- Initial trial nail spacing: $S_H = S_V = 1.5$ m (typical)

SOLUTION TO STUDENT EXERCISE 15

SIMPLIFIED DESIGN CHART PROCEDURE
(Section 8.2.4)

Step 1

- Select Appropriate Design Charts

  Face Batter Angle: 10°

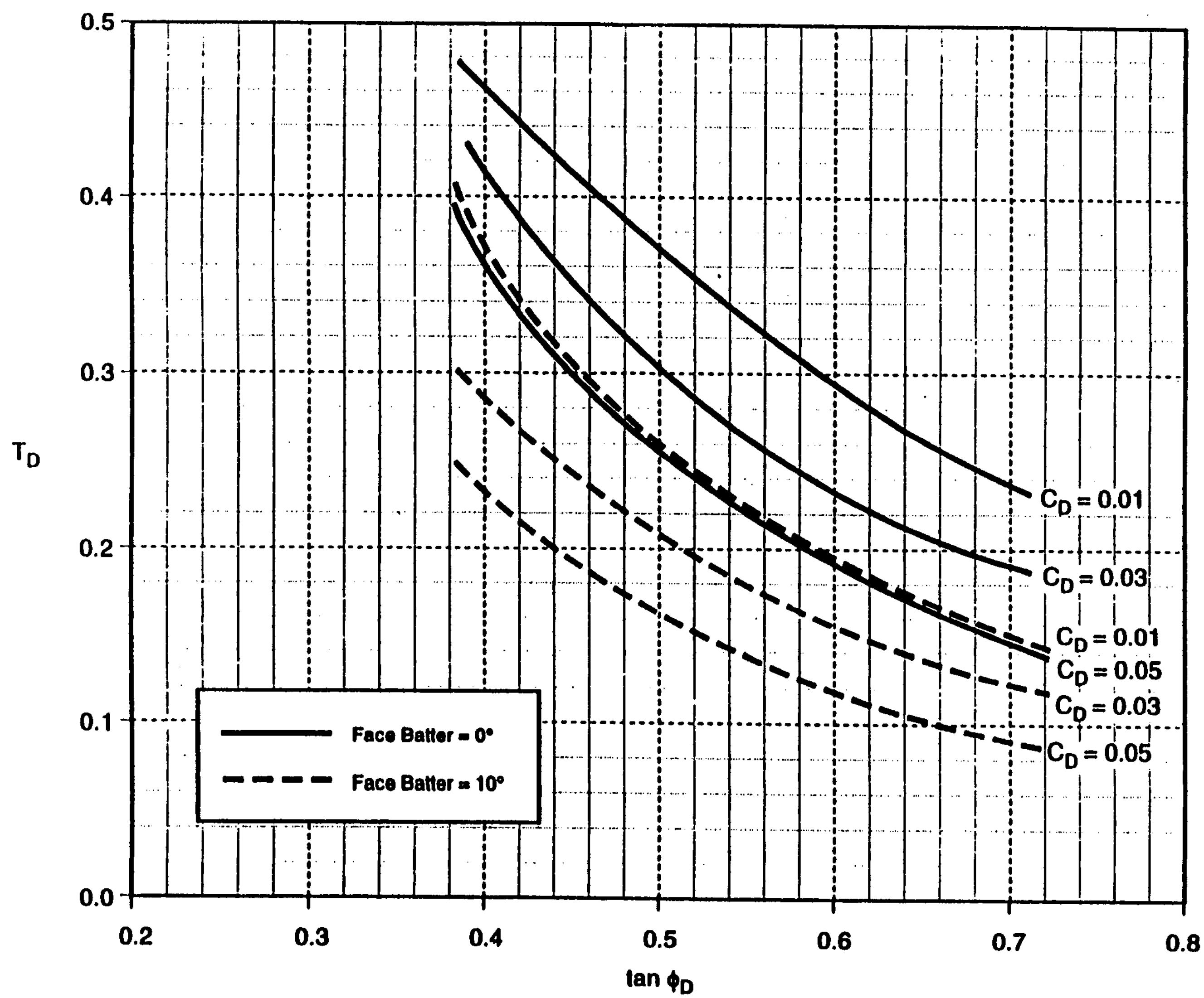
  Backslope Angle: 20° (conservative)

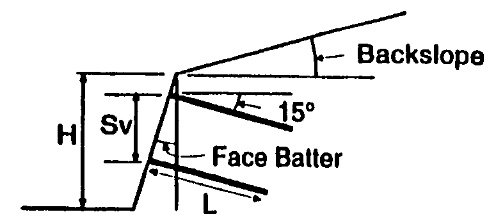
  Use design charts shown in ***Figures 8-16(a) and 8-16(c).***

  These are shown here as Figures S15-2 and S15-3, respectively.

Student Exercise 15 — Figure S15-2

Design Chart 3A   Backslope = 20°: Figure 8-16(a) of Manual





$$\tan \phi_D = \frac{\tan \phi_u}{F\phi}$$

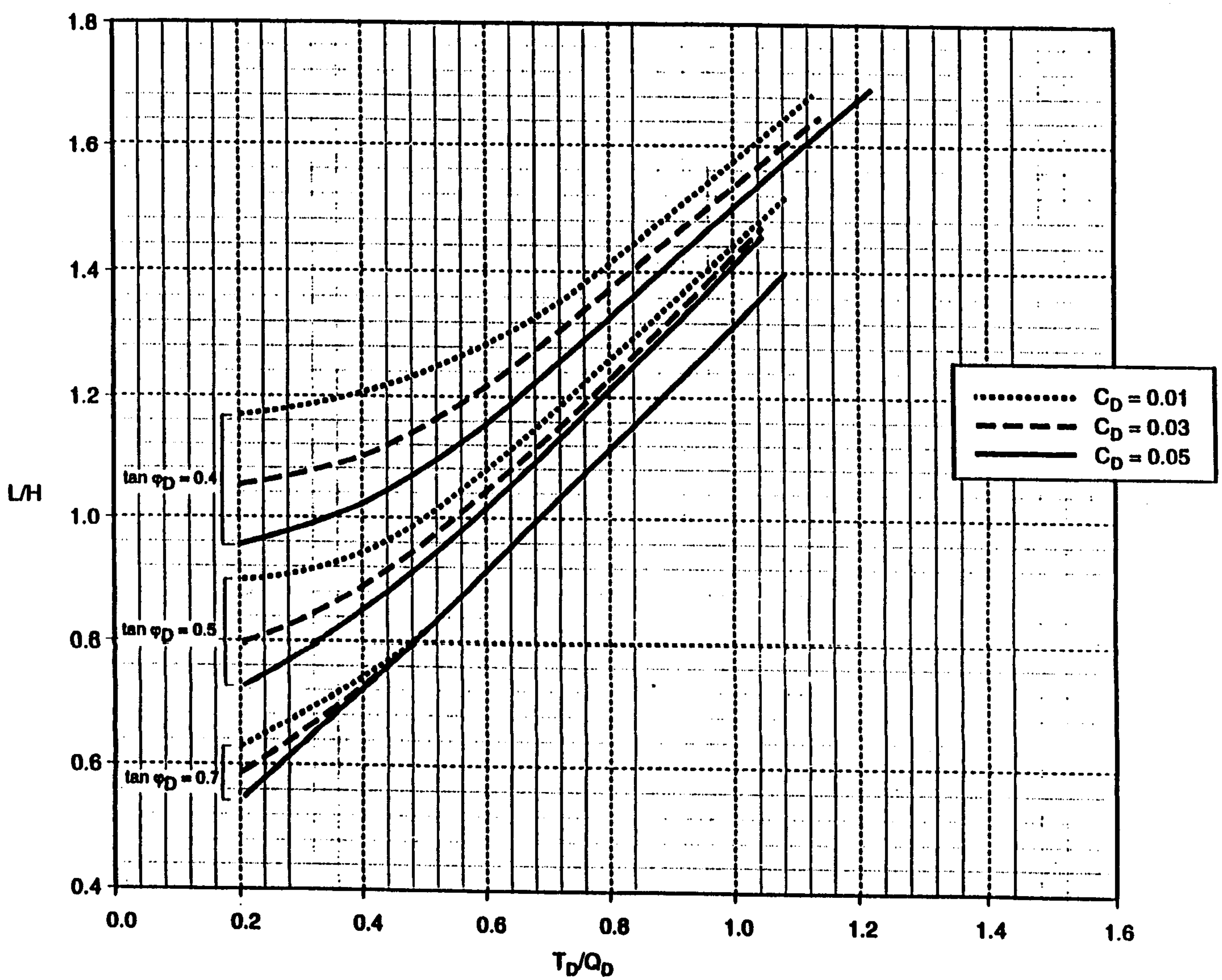
$C_D = c_u/(F_c \gamma H)$

$Q_D = \alpha_Q Q_u/(\gamma S_V S_H)$

$T_D = \alpha_N T_{NN}/(\gamma H S_V S_H)$

Student Exercise 15 — Figure S15-3

Design Chart 3C Backslope = 20°: Figure 8-16(c) of Manual



Step 2

- Compute Factored Soil Friction Angle, ϕ_D:

$\phi_D = \tan^{-1}[\tan(\phi_U)/F_\phi]$ ***(Equation 8-7)***

$= \tan^{-1}[\tan(34°)/1.35]$

$= 26.5°$

$\tan\phi_D = \tan(26.5°) = 0.5$

Note:

F_ϕ = Global F.S. applied to soil friction strength

= 1.35 for AASHTO Load Group I ***(Table 8-5)***

- Compute Dimensionless Factored Soil Cohesion, C_D:

$C_D = c_U/(F_c \gamma H)$ ***(Equation 8-8)***

$= (5\ kN/m^2)/[1.35(18\ kN/m^3)(9.5\ m)]$

$= 0.022$

Note:

$F_c =$ global F.S. applied to soil cohesive strength

$= 1.35$ for AASHTO Load Group I ***(Table 8-5)***

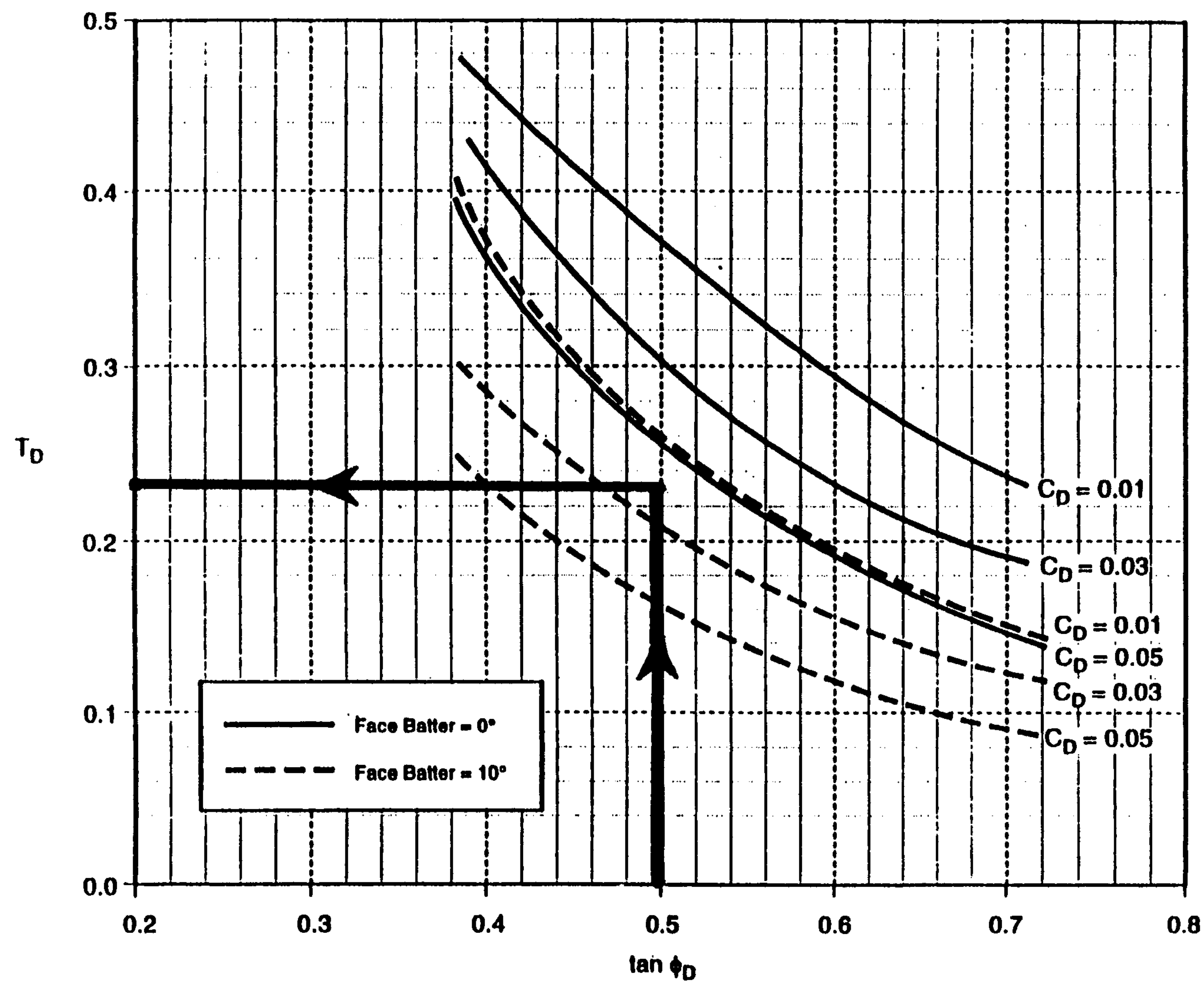
- Determine Dimensionless Nail Strength Capacity, T_D:

For $\tan\phi_D = 0.5$ and $C_D = 0.022$

$\Rightarrow T_D \approx 0.23$ ***(Figure 8-28(a))***

Student Exercise 15 — Figure S15-4

Determination of T_D:Figure 8-28(a) of Manual



Step 3

- Determine Required Nominal Nail Tensile Strength, T_{NN}:

$$T_D = \alpha_N T_{NN}/(\gamma H S_V S_H)$$ ***(Equation 8-9)***

$$T_{NN} = \gamma H S_V S_H T_D/\alpha_N$$

$$= (18\ \text{kN/m}^3)(9.5\ \text{m})(1.5\ \text{m})(1.5\ \text{m})(0.23)/0.55$$

$$= 161\ \text{kN}$$

Note:

α_N = nail tendon tensile strength factor

= 0.55 for AASHTO Load Group I ***(Table 8-5)***

- Determine Reinforcing Bar Size (Grade 420 MPa):

Compute Required Nominal Area, A_{req}

$$A_{req} = T_{NN}/(420\text{MPa})$$

$$= 161 \text{ kN}/(420 \times 1{,}000 \text{ kN/m}^2)$$

$$= 0.000383 \text{ m}^2$$

$$= 383 \text{ mm}^2$$

Use soft Metric No. 25 bars (corresponding to standard bar size No. 8)

$$A_{No.\,25} = 510 \text{ mm}^2 > 383 \text{ mm}^2 \qquad \text{OK}$$

Step 4

- Compute Dimensionless Nail Pullout Resistance, Q_D:

$Q_D = \alpha_Q Q_U/(\gamma S_V S_H)$ ***(Equation 8-10)***

$= (0.50)(60 \text{ kN/m})/[(18 \text{ kN/m}^3)(1.5 \text{ m})(1.5 \text{ m})]$

$= 0.74$

Note:

α_Q=nail pullout resistance factor

=0.50 for AASHTO Load Group I ***(Table 8-5)***

- Compute Ratio of T_D/Q_D:

$T_D/Q_D = 0.23/0.74$

$= 0.31$

- Determine Required Nail Length, L:

For $T_D/Q_D = 0.31$, $\tan\phi_D = 0.5$, and $C_D = 0.022$

$\Rightarrow$ $L/H \approx 0.87$ ***(Figure 8-28(b))***

$$\Rightarrow \quad L = 0.87(H)$$

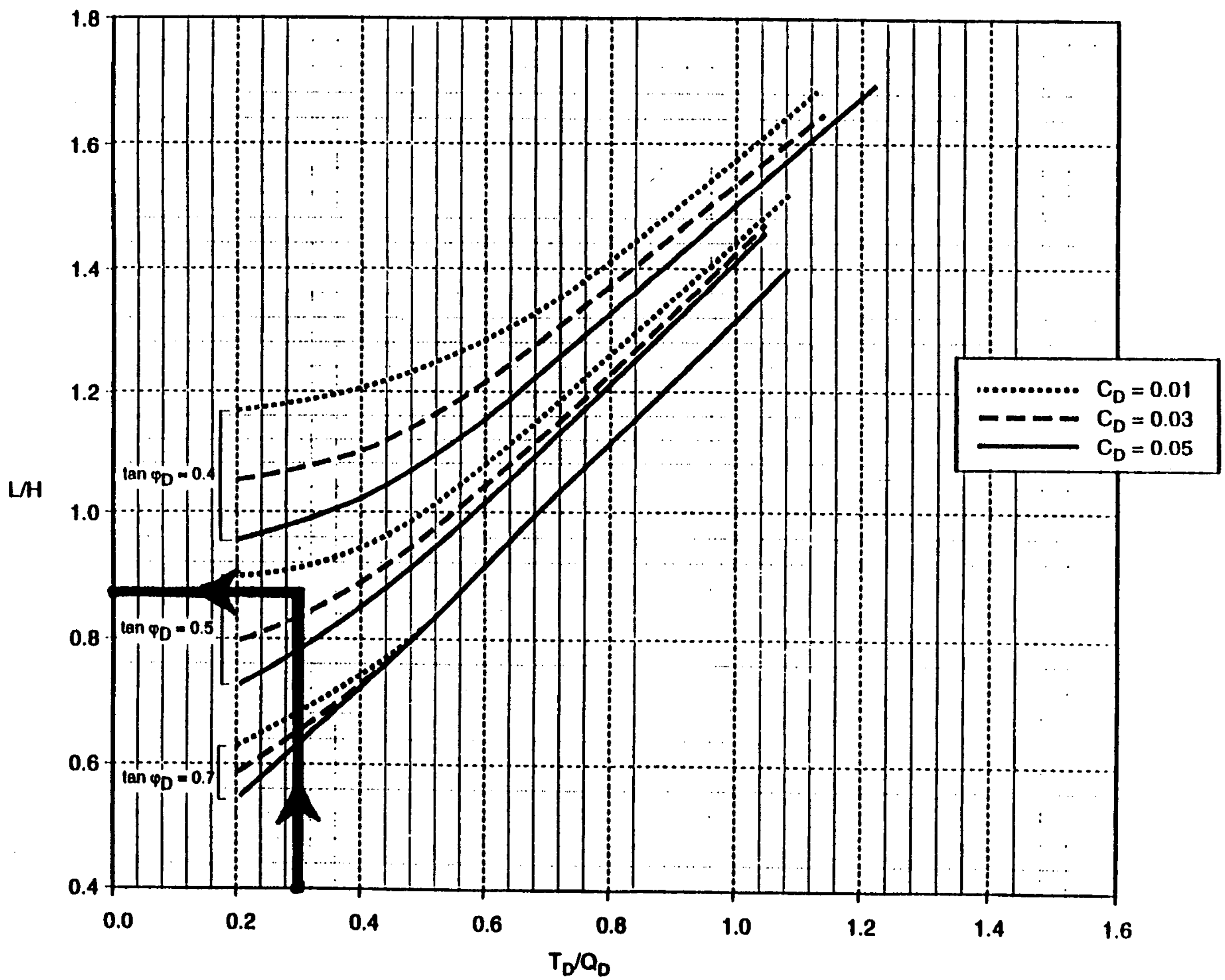
$$= (0.87)(9.5\ m)$$

$$= 8.3\ m$$

Student Exercise 15

FigureS15-5

Determination of L/H : Figure 8-28(b) of Manual

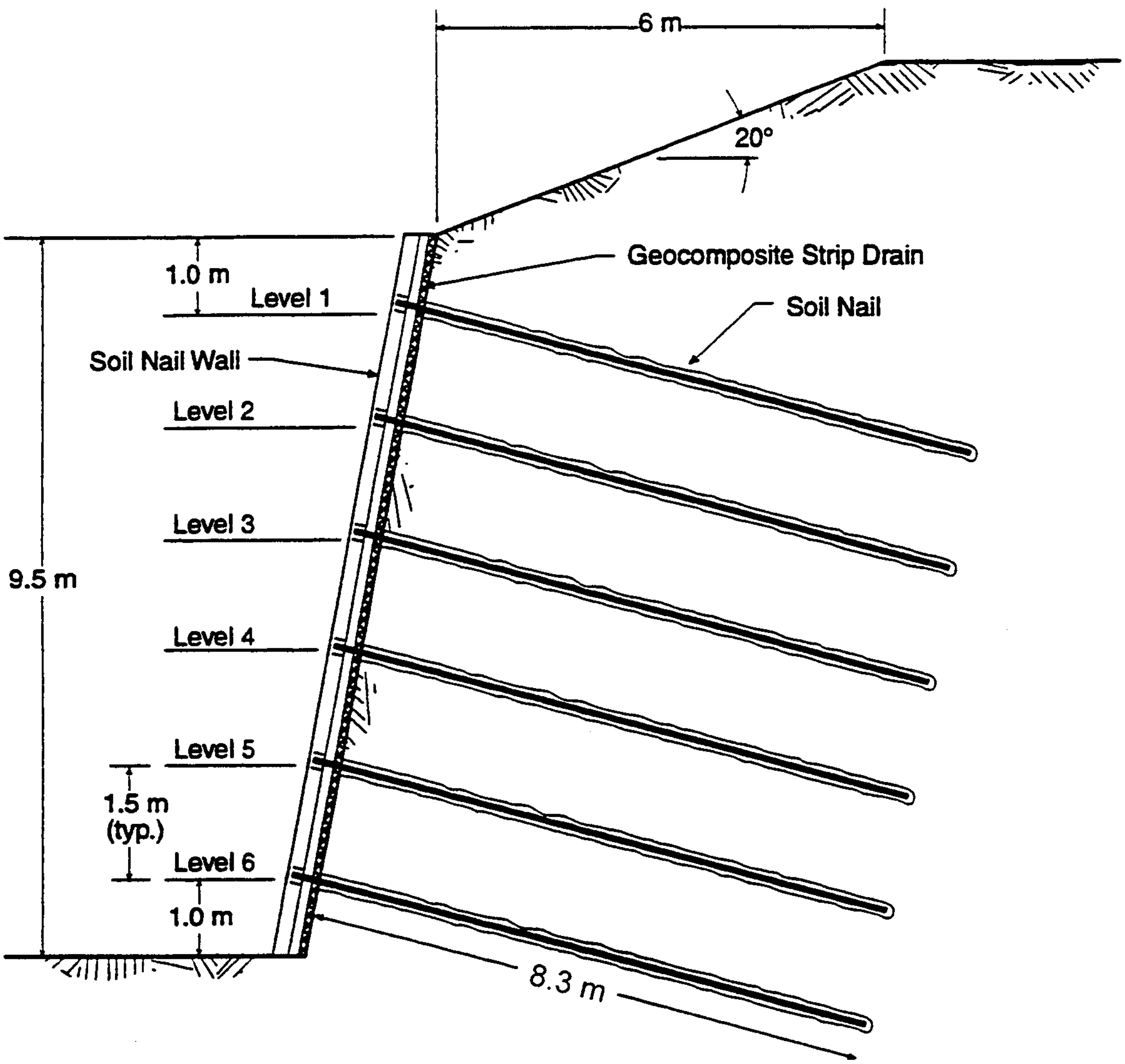


SUMMARY

- Nail Length : 8.3 m (use uniform length)
- Reinforcing Bars: No. 25, Grade 420 (Soft Metric Designation)
- Nail Spacing: $S_V = S_H = 1.5$ m
- Nail Inclination Angle: 15°

See Figure S15-6 for design section based on the simplified design chart procedure

Student Exercise 15
Figure S15-6



STUDENT EXERCISE 16

Statement

To build a road embankment adjacent to a creek, an earth-retaining wall is needed to allow construction of the embankment with a near vertical side slope and avoid encroachment on the wetland. The function of the road is to provide temporary access to remote areas while a permanent highway is built nearby. The embankment and its retaining wall will be designed for a temporary life of 5 years, but with minimum maintenance requirement.

The site lies in a U.S. national forest, thus, the constructed project has to meet strict environmental and aesthetic requirements. Based on the roadway profile and the site topography, the required wall height varies along the alignment, reaching 10 m in certain sections. The soil consists of medium dense silty sand, with zones of soft compressible silty clays that may cause long-term differential settlement problems.

Assignments

1. Select weighting factors from 1 to 3 for the wall selection factors listed on the selection matrix.
2. Using Tables 10-1 and 10-2 perform initial screening and select potential alternatives.
3. For each wall alternative considered assign an initial qualitative rating from 1 to 4 based on each wall selection factor.
4. Calculate the weighted ratings by multiplying the initial rating by the weighting factors.
5. Assign a final score for each wall alternative.

Manual Reference:

Section 10.3.2

Tables 10-1 and 10-2

TABLE S 16-1
SELECTION MATRIX

Project	Selection Factor										Total Score
Weighting Factors											
Wall Alternative	Ground	Ground-water	Construction	Right-of-Way	Aesthetics	Environment	Durability	Cost	Contracting	Tradition	

* Initial Rating (1 to 4)
** Weighted Rating

TABLE S 16-2
SELECTION MATRIX

Project	Selection Factor										Total Score
Weighting Factors	3	1	2	2	2	3	2	3	1	1	
Wall Alternative	Ground	Ground-water	Construction	Right-of-Way	Aesthetics	Environment	Durability	Cost	Contracting	Tradition	

* Initial Rating (1 to 4)
** Weighted Rating

TABLE S 16-3

SELECTION MATRIX

Project	Selection Factor										Total Score
Weighting Factors	3	1	2	2	2	3	2	3	1	1	
Wall Alternative	Ground	Ground-water	Construction	Right-of- Way	Aesthetics	Environment	Durability	Cost	Contracting	Tradition	
Reinforced Soil Wall											
Geotextile Wall											
Gabion Wall											
Bin Wall											
Concrete Module Wall											
Cast-in-Place Concrete											

* Initial Rating (1 to 4)
** Weighted Rating